THE DEFORMATION OF THE EARTH'S CRUST

AN INDUCTIVE APPROACH TO THE PROBLEMS OF DIASTROPHISM

By Walter H. Bucher, Ph.D.

With A New Preface

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To my father

DR. A. J. BUCHER

in sincere gratitude

PREFACE TO THE AUTHORIZED REISSUE OF THE ORIGINAL EDITION OF 1933

IT is possible to give permission to reissue the "Deformation of the Earth's Crust" in its original form after twenty-five years, in spite of the enormous increase in knowledge of regional geology in all continents and the addition of much new geophysical information, because the book separates sharply "essential geological facts of a general nature" (called "laws") from personal interpretations. Apart from desirable changes in wording and emphasis, the "laws" as phrased in 1933 still hold good. "The reader is invited to test the soundness of the laws by his own field experience, and then to devise other, perhaps better, interpretations which will be consistent with all. The synthesis of his own interpretations will yield each reader such satisfaction as is possible at the present undeveloped state of geological knowledge." This paragraph near the opening of Chapter XVI still holds good.

In the preface to the original edition, the writer took care to point out that his personal attempts at interpretations, formulated as "opinions," were purely tentative, "good to him only as long as nothing in sight seems better." They were presented, not to advertise personal bias, but to imbue the cold facts with that "atmosphere of excitement" which, "arising from imaginative considerations, transforms knowledge." They will serve that purpose even better when the reader realizes that the writer has found it necessary to abandon the idea that "the crust is subject alternately to tensile and to compressive stresses, caused by alternating swelling and shrinking of subcrustal matter," (p. 477). The three "laws" which had led to this interpretation ("laws" 16, 20, 37) are as valid as ever. But they demand another explanation. The more we learn about the incidence in time of tensile and compressive deformation in the crust, the more it becomes plain that these two types of deformation cannot represent a world-wide rhythm.

Only very recently has the writer found a line of thought that seems to go a long way towards a satisfactory explanation. It is sketched briefly in two papers:

"The Role of Gravity in Orogenesis": Geol. Soc. Am., Bull., vol. 67, 1956, pp. 1295-1318, (more especially, pp. 1311-1316).

"Modellversuche und Gedanken uber das Wesen der Orogenese" in: Geotektonisches Symposium zu Ehren von Hans Stille, Stuttgart, 1956, pp. 396-410.

In spite of renewed interest in the concept of "continental drift," the writer has so far not found it necessary to change his negative attitude on this controversial issue. The biological reasons for this stand are given on pages 102-111. The geologicial reasons appear on pages 42-43; 73-76; 86-87; 272-273; 382-383; 457-460; and 461-464. For a more recent account, see the writer's paper, "Continental Drift Versus Land Bridges": Bull., Am. Mus. of Natural History, vol. 99, art. 3, 1952, pp. 93-103.

Access to much of the new information that the last twenty-five years have brought is offered in the papers and the bibliographies which comprise the symposium on the "Crust of the Earth." This symposium was organized by the Department of Geology of Columbia University as its contribution to the Bicentennial of the University in 1954 and published under the able leadership of Professor Arie Poldervaart by the Geological Society of America as Special Paper No. 62, 1955, 762 pages.

From these and from hundreds of papers that appear each year, a number of additional "laws" will ultimately be formulated and added to those contained in this book. If they are valid, every one of these laws must be adequately covered by any hypothesis before it deserves general acceptance as scientific theory. Therein lies the value of these "laws".* They provide a touchstone for every man's opinion concerning crustal deformation, and the only possible basis for the inductive approach to the problem, which, in the end, is the only method known to science.

*For an explanation of the sense in which the use of "laws" can be justified, see Bucher, W. H., The Concept of Natural Law in Geology: Science, vol. 84, 1936, pp. 491-498.

PREFACE

"Life nowadays consists of adventures among generalizations."
H. G. Wells, in *The Research Magnificent.*

THIS book comprises an attempt to assemble all essential geological facts of a general nature that bear on the problem of crustal deformation and to derive from them inductively a hypothetical picture of the mechanics of diastrophism that is consistent with them all. The facts are given in the form of carefully worded generalizations which are designated as "laws."

Most of these "laws" require further testing. Some may prove untenable. Although as yet of uncertain value, they are here cast into the form of "laws" in order to stimulate critical penetration of the vast body of information that is being accumulated. Not until we have succeeded in the formulation of a body of specific laws, which are recognized as valid by all, can we expect to arrive at an intrinsically satisfactory solution of the problems of geotectonics.

The writer has been advised to use the more cautious term "theses" instead of "laws." But in common language a thesis is too much a matter of individual conviction to make the word serviceable here. Too much of the geotectonic literature of the past was concerned with the theses of men rather than with laws of nature.

For each of the "laws," one or several examples are given in sufficient detail to enable the reader to judge for himself the nature of the facts generalized in the "law." This form of exposition renders the book useful to advanced university students whose needs were kept in mind, although the book was not designed as a text-book.

From the basic generalizations, or "laws," hypothetical views are developed step by step based on interpretations of the laws in terms of physical processes. Premature as many of these attempts at interpretation may seem, we need them in our search for the concrete facts and the basic generalizations, "laws." They keep alive that "atmosphere of excitement," which, "arising from imaginative considerations, transforms knowledge." In which "a fact is no longer a bare fact; it is invested with all its possibilities. It is no longer a burden

on the memory; it is energizing as the poet of our dreams, and as the architect of our purposes."[1]

The progress of reasoning is interrupted now and then by critical discussions of conflicting ideas. These are given space only insofar as seemed necessary in order to clear the path for further steps of reasoning. No attempt is made to present a picture of the multitude of hypotheses that have been published.[2]

In the last chapter the essential facts, inferences, and hypothetical assumptions are presented in connected form. But the reader should remember that the resulting hypothetical picture is of value only so far as the "laws" on which it is based are valid and the logical steps by which inferences were drawn and assumptions introduced are sound. The writer himself considers his hypothetical picture as merely tentative, good to him only as long as nothing in sight seems better.

The reader is therefore urged to direct his critical study to the main body of the book, to the facts used and to the logical steps taken. The facts especially, as formulated in the "laws," should be criticized and either recognized or rejected openly by everyone who, by experience and inclination, is in a position to check them against first-hand information in his own corner of the world. In such a way alone can a body of recognized facts be created, without which there can be no real insight into the nature of diastrophism.

The writer expects his logic and his hypothetical ideas to be scrutinized as severely and, if found wanting, rejected as determinately as he has done with the ideas of others. We can hope to make headway in our search for a road to understanding only by taking the task of critical reasoning as seriously as we take that of accurate observation.

In the preparation of this book, the writer received valuable information and advice from many fellow-geologists and friends to all of whom he wishes to express his gratitude. He owes special thanks to Drs. Bruce L. Clark, Sidney Powers, and W. A. J. M. van Water-

[1] A. N. Whitehead, "Universities and Their Function," *Atlantic Monthly*, May 1928, p. 639.

[2] For good summaries see: Fr. Nölke, *Geotektonische Hypothesen*, Berlin, 1924; L. Rüger, "Geotektonische Hypothesen," *Geographische Zeitschrift*, Vol. 37, 1931, pp. 577-97. The latter extends to Haarmann's *Ossillations Theorie* (1930), but not to J. S. DeLury's "The Auto-traction Hypothesis of Crustal Evolution," *Contrib. from the Department of Geol. and Min., Univ. of Manitoba*, Winnipeg, 1931.

schoot van der Gracht, who generously permitted him to use maps, charts, and manuscripts of important papers in advance of publication,[8] and to Drs. Chas. H. Behre, Wm. Bowie, A. F. Buddington, L. Brand, N. M. Fenneman, T. S. Lovering and W. P. Woodring for critical reading of certain chapters or parts of chapters. The writer is especially indebted to two friends who read the whole manuscript, giving much valuable advice as to contents and form: Dr. Taylor Thom and Mrs. L. S. Brand.

My thanks are also due to the Dean, Dr. L. T. More, for advantages afforded me as Fellow of the Graduate School of the University of Cincinnati.

An outline of the contents of this book was presented upon invitation before the graduate students of the Department of Geology of Princeton University in November 1928. The encouragement which this invitation afforded and the courtesy and efficiency shown later by the Princeton University Press in the publication of this book are remembered with gratitude.

[8] The papers referred to have appeared in print recently.

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"The writer no longer subscribes to the opinion that 'the crust is subject alternately to tensile and to compressive stresses, caused by alternating swelling and shrinking of subcrustal matter' (p. 477). For a more promising attempt to account for laws 16, 20 and 37 see the two papers cited in the Preface to the Authorized Reissue."

CHAPTER I

THE MOBILE BELTS

"Men are prone to take the familiar as a matter of course and to ask the meaning of the strange only."
G. K. Gilbert, in *Studies of Basin-Range Structure.*

I. ELEVATION AND DEPRESSION

Deflection of surface. The most general observation concerning crustal deformation on the earth is expressed in the first law.

Law 1. Aside from the effects of erosion and deposition, the earth's surface deviates from the relatively simple form of an ellipsoid, to which it may be referred, through outward (upward) and inward (downward) deflections.

Here, as in all that follows, we are concerned only with those forms of the earth's surface which are the result of forces acting from within the earth, that is, from an actual deformation of the earth's crust.[1] Erosion mars elevations and deposition masks depressions. Some structural features, moreover, and the corresponding surface forms, are merely secondary, superficial effects of the crustal deformation produced by differential movements in the outer mantle of sediments. Both—surface forms and surface structures—therefore require analytical study before the direction and nature of the actual crustal deformation can be read from them.

The surface of the crust, to which this first law applies, is, then, an abstract concept which differs, from point to point, more or less widely from the actual surface of the earth. One convenient reference level for the purpose of estimating the algebraic sum of crustal deformations for the whole of post-Lipalian[2] time is the attitude of the very widespread pre-Cambrian erosion surface. This reference level becomes inadequate where later erosion has had access to it. The latest crustal deformations which erosion has not yet had time to

[1] The word "crust" is here used, for the time being, in the vague sense of an outermost layer of the earth to which those changes must be confined which find expression in surface form and rock structure. Later it will be defined adequately (p. 39).

[2] Lipalian interval = post-Proterozoic, pre-Cambrian interval. See C. D. Walcott, "Abrupt Appearance of the Cambrian Fauna on the North American Continent," *Smithsonian Misc. Coll.*, Vol. 57, 1910, pp. 1-16.

wipe out are expressed in the present topography. Again the evidence is qualitative rather than quantitative, since we have not learned yet to appraise correctly the actual amount of erosion accomplished at a given point.

In the oceans, where erosion certainly ceases to be an important factor below the one-hundred-fathom line, sedimentation continues to conceal the true form of crustal deformation. The continental shelves themselves do not necessarily reflect the shape of the crustal surface. No one knows what part of them is a huge submarine terrace built of relatively recent sediments. Even the great depths of the "deeps" may be less than the actual downward crustal deformation, hidden by an unknown amount of sediment.

Although somewhat abstract and vague, the concept of deformation that involves the earth's crust as contrasted with alterations of the surface or local disturbances of the surficial mantle of sediments, is eminently useful.

Turning now to the contents of the first law, it is important to realize that it is not inherently necessary that deflections in both directions be present on the deformed surface of an ellipsoid. In the laboratory experiments on folding which have been performed by geologists with the aid of compression boxes, or with paraffin-covered rubber sheets, only upward deflections take place. Yet geologists have not hesitated to apply their results at once to the larger aspects of the earth's surface where, in contrast to the conditions of the experiments, downward deflections rival in importance the upstanding folds. In the coexistence of both types of deflections we face the real problem of the nature of the deflecting forces.

Movement reversible.

Law 2. In the progress of crustal deformation, the direction of radial displacement is reversible.

This law expresses a commonplace of geological knowledge, and yet it seems to be easily forgotten when geophysical problems are discussed. The standard example which is presented to all freshmen in American colleges is that of the section exposed in the Grand Canyon of Arizona. Here the base of the Proterozoic Unkar and Chuar series is a typical plain of denudation cutting across the nearly vertical crys-

talline rocks of the Archeozoic.[3] Such a well developed peneplain cannot well have formed more than a few hundred feet above sea level, depending on the distance from the sea. Taking as starting point this pre-Unkar peneplain, with its position not far from sea level, we see it depressed a first time below sea level to a depth of at least two miles, the thickness of the sediments of the Algonkian systems.[4] Then warping, accompanied by faulting, carried the reference peneplain again above sea level. This is the first great reversal of the direction of radial displacement exhibited in the canyon. A second remarkably even peneplain was cut across the tilted beds, the post-Chuar peneplain. Only occasional low monadnocks rise up from its level surface into the Cambrian beds above. A fault with a throw of 1,200 to 1,300 feet is seen levelled completely, the undisturbed Cambrian sandstone cutting off sharply the displaced beds below.[5]

The second reversal carried the post-Chuar peneplain beneath the waters of the Cambrian sea. The Paleozoic, Mesozoic, and Tertiary strata that were subsequently deposited on this sinking surface measure near three miles in thickness.[6] Of these certainly more than two miles were laid down below sea level. To that extent at least the reference level was lowered in this second downward deflection. But today it lies again over three thousand feet above sea level. This indicates the third great reversal of radial displacement. In neither of the two great up and down movements was there a strong folding of the rocks; in the second, even warping was at a minimum.

To give one other conspicuous illustration we turn to the famous radiolarian cherts that are so widely distributed throughout the

[3] For a generalized section showing the great thickness of the post-Algonkian sediments that once covered the Grand Canyon region, see W. M. Davis, "The Grand Canyon of Colorado," *Bull. Mus. Comp. Zool. Harvard, Geol. Ser.*, Vol. 5, 1901, p. 116, Fig. 2.

[4] C. D. Walcott, "Pre-Cambrian Igneous Rocks of the Unkar Terrane, Grand Canyon of the Colorado, Arizona," *U.S. Geol. Survey, Fourteenth Ann. Rept.*, Part 2, p. 512, gives a section of the "Grand Canyon Series" (Unkar and Chuar groups) measuring 11,950 feet.

[5] C. E. Dutton, "Tertiary History of the Grand Canyon District," *U.S. Geol. Survey, Mon. I*, 1882, p. 179. For details of minor faulting in the pre-Cambrian rocks, see L. F. Noble, "The Shinumo Quadrangle," *U.S. Geol. Survey, Bull. 549*, 1914, p. 77, and cross-sections on Pl. 1.

[6] In round figures: 4,500 feet of Cambrian and Carboniferous beds; 9,000 to 10,000 feet of Mesozoic beds and, perhaps, 1,000 to 1,200 feet of lower Eocene. Quoted from chapter on "the great unconformity" in C. E. Dutton, "Tertiary History of the Grand Canyon District," *U.S. Geol. Survey, Mon. I*, 1882, p. 181.

Alpine mountain chains of southern Europe and Asia, the realm of the Mesozoic Tethys. The conviction is widespread that they represent true deposits of the deep sea, comparable to the radiolarian oozes of modern oceans which are closely associated with the red clay of the great depths.[7] The proof of the deep-sea nature of these radiolarian cherts is not compelling, but is not easily dismissed.[8] Suess, for instance, thinks that the radiolarian cherts of the Pennine (= "lepontine") *decken* of the Alps must have been deposited at a depth that "can hardly have been less than 4,000 meters" (13,000 feet).[9] If we accept this view for the moment, it furnishes a picturesque illustration of the law we are discussing. In the heart of the Alps, radiolarian cherts are found at great elevations. On Piz Lischanna, for instance, which towers above the south side of the upper Inn Valley near the eastern border of Switzerland, they lie at an elevation of little less than ten thousand feet above sea level. Similar illustrations could be quoted from many parts of the Alps and from most other mountain systems in the domain of the old Tethys. The radiolarian cherts of the Franciscan series of our Coast Ranges and of the west slope of the Sierra Nevada are the American equivalents but have been carried to less exalted heights.

Deep-sea sediments in mountain peaks; an epigrammatic statement of the law of the reversibility of radial displacement. If the radiolarian cherts of these Jurassic seas of the old and new world are not deep-sea sediments, their testimony remains unchanged. For they belong to sedimentary series, mostly marine, several miles thick in many parts. The towering position of pelagic sediments in mountain ranges of Alpine height is as significant as it is familiar.

2. "Welts" and "Furrows"

Linear versus non-linear surface elements.

Law 3. In ground plan, the forms of crustal elevations and depressions represent two types. First, elevations and depressions which are essentially equidimensional (swells and basins); and second, others that show a distinct linear development with one horizontal dimension decidedly greater than the other (welts and furrows).

[7] E. Suess, *The Face of the Earth* (trans. by Sollas and Sollas), Vol. IV, p. 563.

[8] G. Steinmann, "Die geologische Bedeutung der Tiefseebildungen und der ophiolitischen Eruptiva," *Ber. Naturf. Ges. Freiburg*, Vol. 16, 1905, pp. 44-65.

[9] E. Suess, *The Face of the Earth*, Vol. IV, p. 564.

We shall speak of these two groups as the linear and non-linear types of crustal deformation. The words "shield" and "basin" have long been used for some forms of the non-linear type. The word "shield," however, has acquired an implication of large dimension ("Canadian Shield") and is, therefore, not really useful. Recently Schuchert[10] has extended the use of the word "swell" to all "domed areas within the neutral or nuclear areas." It is clearly devoid both of a connotation of size and of a suggestion of origin. It also distinctly implies the opposite of a linear outline. The word "basin" is definitely entrenched in geological and geographical literature ("Michigan Basin," "Congo Basin"). In these pages we shall use "swell" and "basin" for all non-linear surface forms produced by crustal deformation.[11]

For the linear surface elements produced by crustal deformation we shall here use the words "welts" and "furrows." The word "welt" combines the image of a ridge raised on the skin (a wale) with that of a raised border. In this sense Hobbs, for instance, speaks of the "gigantic welt of the Himalayas." Both words are free from any genetic implications and also from connotations of size. Both refer definitely to linear elements.

That this loose classification into "swells" and "basins," "welts" and "furrows" is not idle playing with words becomes apparent in the fourth law.

Excessive deformation.

Law 4. On the present face of the earth, excessive heights and excessive depths of crustal deformation are limited to "welts" and "furrows," that is, to elevations and depressions of distinctly linear outline.

This law applies to elevations produced by crustal deformation, not to topographical differences produced by erosion or by the accumulation of products of volcanic activity or of sediments. Such lofty volcanic peaks as Kilima Njaro (19,320 feet)[12] and Mt. Kenya

[10] Charles Schuchert, "Sites and Nature of the North American Geosynclines," *Bull. Geol. Soc. America*, Vol. 34, 1928, p. 165.

[11] In his first paper on crustal deformation, the writer used the word "swell" for linear elements. He was ignorant, at the time, of the current implications of the word. "The Pattern of the Earth's Mobile Belts," *Jour. Geol.*, Vol. 32, 1924, pp. 265-90.

[12] Elevations throughout this book are taken from J. G. Bartholomew's *The Times Survey Atlas of the World*, London, 1922, unless stated otherwise.

(17,040 feet), much of the picturesque lava plateaus of Abyssinia on the otherwise rather monotonous face of Africa, and many a gigantic pile of lavas that rises as an island from the deep sea, must be stricken from the bathy-orographical map of the world when we look for the facts comprised in this law.

The most tangible expression of crustal elevation is seen in the regions in which metamorphic and intrusive rocks have been raised sufficiently to have been exposed by erosion. All excessive elevations of these normally rather deep-seated rocks are strictly limited to "welts," that is, long and narrow belts of uplift. Mt. Everest raises its final pyramid of very fine-grained and compact quartz and biotite-bearing calcareous schists to the elevation of 29,002 feet above the foliated and banded biotite gneiss of the crystalline Himalayan zone.[13] Europe reaches its highest elevation in Mont Blanc (15,782 feet), one of the finest examples of an ancient granite with its mantle of schists lifted above a thick series of Mesozoic and Cenozoic rocks.

The Australian region culminates in the metamorphic ranges[14] of the Southern Alps of New Zealand, where Mt. Cook rises to 12,349 feet. From the highest part of Illimani (21,030 feet), the best known of the magnificent peaks of the Cordillera Real, "the crowning range of all South America," Sir Martin Conway brought back gneiss and coarse-grained granite.[15] In the Alaska range, the intrusive granite of the peak of Mt. McKinley (20,300 feet) rises above the intensely thrust-faulted and folded Ordovician beds.[16]

These famous highest points of continents were chosen for the sake of emphasis. They are all parts of much more extensive long and

[13] A. M. Heron, "Geological results of the Mount Everest Expedition, 1921," *Geog. Jour.*, Vol. 59, 1922, pp. 418-31 (with geological map opp. p. 480); N. E. Odell, "Observations on the Rocks and Glaciers of Mount Everest," *ibid.*, Vol. 66, 1925, pp. 289-315.

[14] E. A. Fitzgerald, *Climbs in the New Zealand Alps*, London, 1896 (with notes on rocks by T. G. Bonney); P. Marshall, "New Zealand and Adjacent Islands," *Handbuch d. regionalen Geologie*, Heft 5, 1911, pp. 56-7.

[15] Sir Martin Conway, "Explorations in the Bolivian Andes," *Geog. Jour.*, Vol. 14, 1899, pp. 14-38. Quoted from E. Suess-De Margerie, *La Face de la Terre*, Vol. III, p. 1307. Aconcagua, probably the highest peak of the western hemisphere (22,868 feet), on the boundary of Chile and Argentina, is part of a huge overturned fold of Mesozoic trachytic and andesitic lavas, tuffs, and limestones. (According to W. Schiller, *N. Jahrb. f. Min.*, Beil. Bd. XXIV, 1907, Pl. XLVI, reproduced in E. Suess-De Margerie, *La Face de la Terre*, Vol. III, p. 1379.)

[16] A. H. Brooks, "The Mount McKinley Region," *U.S. Geol. Survey, Prof. Paper 70*, 1911.

narrow upward deformations of the crust, true "welts," of which they happen to be at present the culminating points.

We may make a similar use of the greatest recorded ocean depths. A glance at a bathymetric map of the Pacific Ocean[17] shows at once that depths below 24,000 feet are limited to long narrow troughs within much larger "deeps" which comprise all sea bottom below three thousand fathoms. One such pronounced trough parallels the east side of the Philippine Islands from the southern tip of Luzon to beyond Mindanao. In it the greatest known depths have been sounded. Here the German cruiser *Emden*, on April 29, 1927, recorded a depth of at least 34,220 feet (10,430 meters).[18] In the rectangle between the meridians 126° 49′ and 127° 0′ E. and the parallels 9° 42′ and 9° 59′ N., the *Emden* found that 46 out of a total of 335 sonic depth soundings reached depths below 32,800 feet (10,000 meters), all exceeding the greatest known depth in this part of the ocean. This was 32,115 feet found by the *Planet* in 1912, about fifteen statute miles north-northwest from the new record.

In 1924 about fifty-seven statute miles off the coast of Japan, in the famous "Tuscarora" Deep that skirts the arcs of the Japanese and Kurile Islands, the Japanese cruiser *Manchu* sounded a depth of 32,150 feet without striking bottom.[19]

Other excessive depressions have been known much longer. Such are, for instance, the depth of 31,615 feet southeast of Guam, the southernmost of the Ladrone Islands (*Nero*, 1899); 30,930 feet east of the Kermadec Islands and 30,130 feet on the east side of the Tonga Islands (both *Penguin*, 1895).

In the Indian Ocean, the greatest measured depth lies in a narrow trough south of Java (22,960 feet). In the Atlantic Ocean the

[17] For instance, Max Groll, "Tiefenkarten der Ozeane," *Veröff. Instit. f. Meereskunde d. Univ. Berlin*, N.F., Abt. A., H. 2, 1912, Pl. III; or the more generally accessible, more generalized maps in Bartholomew's *Times Atlas* (Pls. CII and CIII).

[18] The depth was obtained by means of the Sonic Depth Finder which, in contrast to the wire sounding, always yields minimum depths. On the basis of corrections of the rate of sound propagation for temperature, pressure, and salinity, H. Maurer has computed the true depth of this point as 35,410 feet (10,793 meters). (*Zeitschr. Ges. f. Erdkunde*, Berlin, 1927, No. 5/6, pp. 339-41.)

[19] *Mitt. Geogr. Ges. Wien*, Vol. 70, 1927, p. 155. The depth of 27,930 feet, sounded in 1874 by the *Tuscarora*, was known for over twenty years as the greatest depth of the ocean.

greatest depth was found in the Brownson Trough[20] close to the northern shore of Puerto Rico (27,972 feet).

These examples serve to show the order of magnitude of the relief produced by crustal deformation in "welts" and "furrows." They also serve to introduce the fifth law.

Welts and furrows associated.

Law 5. On the present face of the earth, "welts" and "furrows" *do not occur* independently, but are closely associated and lie side *by side in relatively long* and narrow belts.

This law is here stated as an expression of existing conditions without regard to traditional ideas concerning causes and sequences of events. We must remember that our definition of welts and furrows is purely descriptive and entirely free from any genetic concepts. Applied to troughs on the sea bottom, the law assumes the well known form that narrow deep-sea troughs are always found comparatively near land.[21] On the continents the law says that great "geosynclinal" depressions border the mountain ranges. We will do well to carry out quantitatively in one or two examples such as a comparison of troughs on the sea bottom and on continental surfaces.

Mountain range and "foredeep." Fig. 1 shows the structural depression that follows the east front of the northern Rocky Mountains in the United States and Canada.[22] Here, as in oceanic deeps, the excessive depths lie in furrows close to the towering mountain ranges. The contours on this map are drawn, however, only at the base of the Cretaceous (on the "Dakota Sand," to be exact). They

[20] The name "Nares Deep" applies to the vast area of deep sea (below 3,000 fathoms) which lies between lat. 18° N. and 34° N., east of the West Indies and the United States. Depths below 4,000 fathoms are limited to this "Porto Rican" or "Brownson" Trough which lies at the southern border of the Nares Deep. See Map 3 and p. 141 in J. Murray and J. Hjort, *The Depths of the Ocean*, London, 1912.

[21] See, for instance, J. Murray and J. Hjort, *The Depths of the Ocean*, London, 1912, p. 137: "All the soundings recorded in depths of over 4,000 fathoms are taken comparatively near land."

[22] R. H. Johnson and L. G. Huntley, *Principles of Oil and Gas Production*, New York (John Wiley and Sons), 1916, p. 246, Fig. 95. Compare also D. B. Dowling, S. E. Slipper, and F. H. McLearn, "Investigations in the Gas and Oil Fields of Alberta, Saskatchewan, and Manitoba," *Canada Geol. Survey, Memoir 116*, Ottawa, 1919, Map Pub. No. 1780.

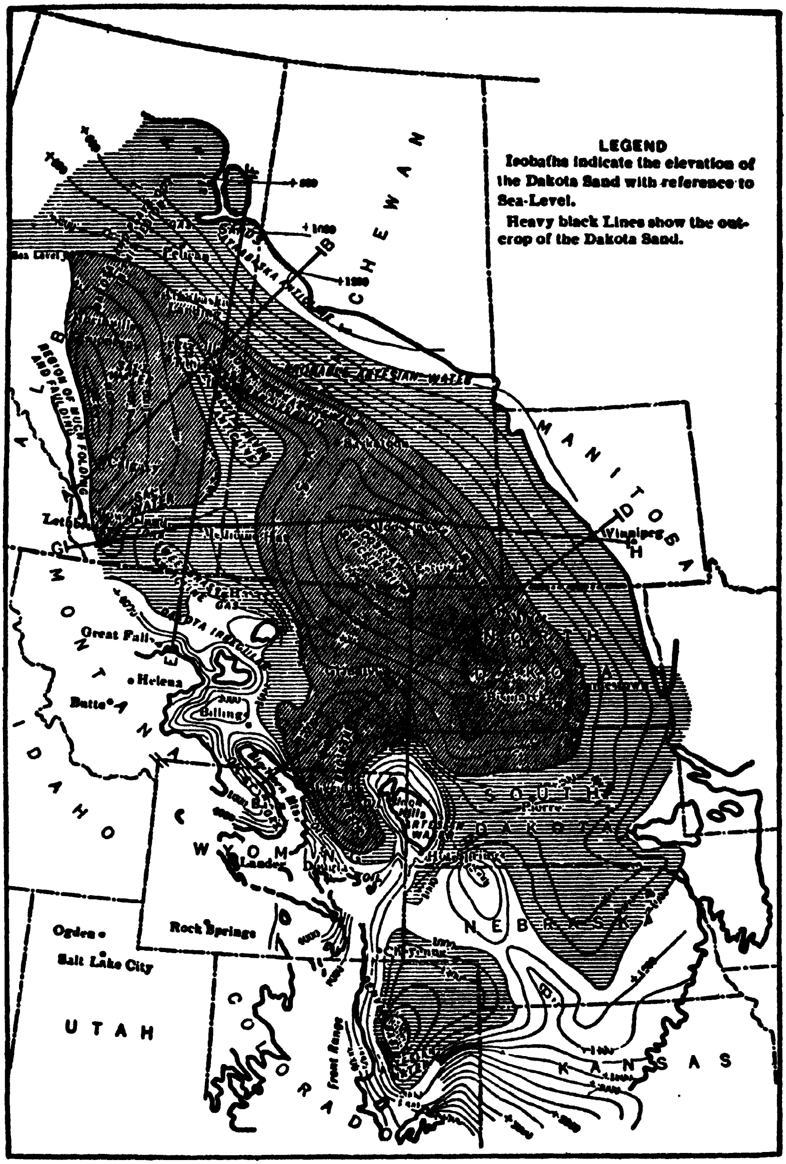


Fig. 1. Tectonic sketch map showing generalized structure of the Dakota sandstone in front of the Rocky Mountains, from Colorado to Alberta.

(R. H. Johnson and L. G. Huntley, 1916; reproduced by permission from *Principles of Oil and Gas Production*, published by John Wiley & Sons, Inc.)

do not give us a correct quantitative picture of the deformation.[23] Thom has estimated the relief from the crest of the Bighorn Mountains to the depths of Powder River Basin on the east as over 20,000 feet, and as over 22,000 feet to the bottom of Bighorn Basin on the west.[24]

Referring to conditions as we now see them, we are certainly justified in speaking of this line of welts and furrows as traversing the continent. The present center of the line of troughs in front of the Bighorn Mountains lies some 880 miles east of the Pacific, a distance like that of St. Louis from the New Jersey shore. To speak of them as "Pacific" is no better than calling the Mississippi embayment south of St. Louis "Atlantic." The displacement along the Rocky Mountain front should, therefore, be measured against the mean continental level, above which the mountains rose and below which the troughs sank. E. Kossinna has recently[25] determined the mean elevation of all continental surface as 755 feet (230 meters) (exclusive of mountains above 1,000 meters = 3,280 feet, and including the shelves down to the edge of the continental shelf —200 meters = —655 feet). Above this mean level the Bighorn Mountains rise to 14,000 feet and the Bighorn Basin drops to —8,000 feet.

For a marine object of comparison let us choose the submerged system that runs in a northeasterly direction into the Pacific from the East Indian Archipelago and reaches above sea level in the Pelew Islands. The curved southeastern front of the Pelew Islands is bordered by a trough over two hundred miles in length, which lies at a depth of over 18,000 feet below sea level. Aside from the greatest depth sounded in it (26,790 feet),[26] the relief from the low island surface to the sea bottom is quite comparable to that of the

[23] See Fig. 1, p. 3, in W. T. Thom, Jr., "The Relation of Deep-seated Faults to the Surface Structural Features of Central Montana," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 7, 1923.

[24] D. F. Hewett and C. T. Lupton, in "Anticlines in the Southern Part of the Big Horn Basin, Wyoming," *U.S. Geol. Survey Bull. 656*, p. 32, give a larger estimate: "The difference in elevation of the pre-Cambrian surface restored over Cloud Peak, which has an elevation of 13,163 feet, and the same surface under the trough of the basin amounts to about 27,000 feet. . . ."

[25] E. Kossinna, "Die Tiefen des Weltmeeres," *Veröff. Inst. f. Meereskunde d. Univ. Berlin*, N.F., Reihe A., H. 9, Berlin, 1921, pp. 35-7.

[26] Bartholomew's *Times Atlas*, Pl. CII.

Rocky Mountain front. Kossinna computed the mean depth of the ocean floors as —14,500 feet (—4,420 meters), that is, of that portion of the ocean bottom which lies below the lower edge of the continental slopes (—8,000 feet), and above the upper edge of the "deeps" (—18,865 feet). Above this mean level, the Pelew Islands rise over 14,500 feet, and below it the furrow drops to a maximum extent of over 12,000 feet.

Rim and bottom of rift valley. There is a long cry from Rocky Mountain structure and foredeeps to the rift valleys of eastern Africa. Yet a glance at the contoured map of central and southern Africa in Bartholomew's *Times Atlas* (Pl. LXX) shows elevations above 5,000 feet strikingly lined up along the two great rift zones which, springing from the north end of Lake Nyasa, extend northward on the east and west sides of Lake Victoria.[27] In the eastern branch, from the latitude of the south end of Lake Victoria north to the Red Sea, the marginal welts are greatly modified by Tertiary and Quaternary volcanics and volcanoes. Along the shores of Lakes Nyasa and Tanganyika, they stand unobscured. They constitute a famous example of the common observation that the edges of "fault troughs" appear uplifted. We shall do well to keep our minds free, for the present, of mechanical interpretations attached to "troughs" or "rifts" and to be content with seeing that they obey the broader law here phrased. For purposes of dimensional comparisons, we may note a few figures. Both Lake Tanganyika and Lake Nyasa show a width which does not exceed forty miles at many points. The distance from crest to crest of the marginal uplifts exceeds fifty miles for considerable distances along both lakes. The present surface of the marginal welts rises well above 6,500 feet at a number of points along both Lake Tanganyika and Lake Nyasa. The greatest known depth in the former, 4,710 feet (1,435 meters), was found nearer the Belgian shore in the southern part of the lake. Since the surface of the lake lies about 2,560 feet (780 meters) above sea level, the bottom of Lake Tanganyika lies at least 2,150 feet (655 meters) below the Indian Ocean.[28] The greatest depth sounded in Lake Nyasa is 2,570

[27] See map, "Great Rift Valley," opposite p. 358, in J. W. Gregory, *The Rift Valleys and Geology of East Africa*, London 1921, or E. Krenkel, *Die Bruchzonen Ostafrikas*, Berlin (Gebr. Borntraeger), 1922, Pl. 1.

[28] E. Krenkel, *op. cit.*, p. 15. It is the second deepest lake on the earth.

feet (783 meters). With its surface 1,565 feet (477 meters) above the sea level, it therefore extends at least 1,000 feet below the level of the Indian Ocean.[29] The greatest known relief in this part of the rift zone, therefore, exceeds 9,000 feet.

For an oceanic object of comparison we turn to the Bartlett Trough in the Caribbean Sea. Woodring's map[30] (Fig. 2) shows this exquisite trough lined for parts of the distance on either side by "welts" which reach above or near sea level in Swan Island and the Bay Islands on the south side, and in the Misteriosa Bank and the Cayman Islands on the north side. Where the trough runs along the edge of the land mass of Cuba, the welt rises as a mountain range, the Sierra Maestra, to a height of 8,397 feet (Punta de Turquina).[31] Again we find the greatest depths in furrows that follow the edges of the trough close to the welts; the greatest depth recorded on Woodring's map lies opposite the Punta de Turquina, at a depth of 21,036 feet. Here, then, we have a furrow about one hundred miles wide between marginal welts with a maximum known relief of 29,400 feet.

The examples here given suffice to show that this fifth law is independent of traditional views of the mechanics involved in a deformation.

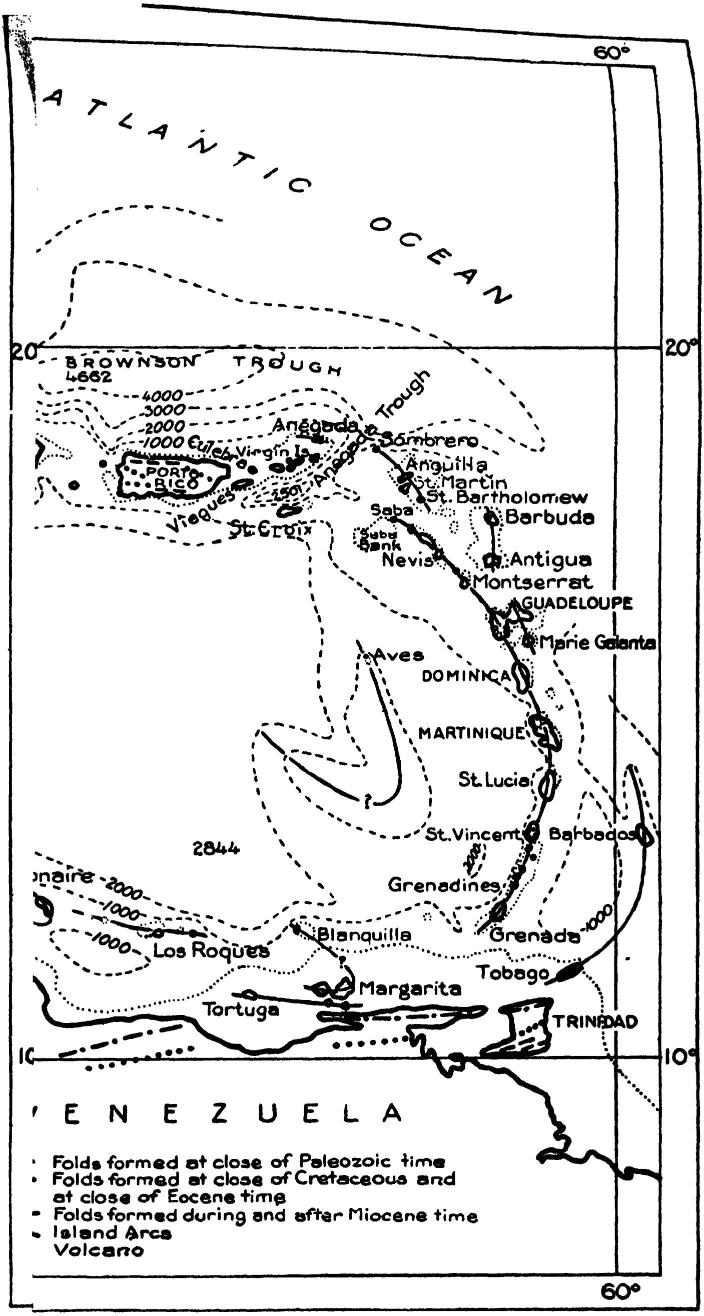
"Foredeeps" and "backdeeps." Before passing on to the next law, one widespread error remains to be corrected. It is not true that "ocean deeps . . . form . . . always only on the outer margin" of island festoons.[32] The Ladrone Deep exists only on the southern half of the island arc. The curved Bougainville Trough on the southeast side of the Island Neu Pommern (= "New Britain"), in the Bismarck Archipelago, skirts only the southeastern half of the fine arc

[29] E. Krenkel, *op. cit.*, p. 25.

[30] W. P. Woodring, "Tectonic Features of the Caribbean Region," *Proc. Third Pan-Pacific Science Congress*, Tokyo, 1926, publ. 1928, pp. 401-31, map, p. 423. See also Stephen Taber, "The Great Fault Troughs of the Antilles," *Jour. Geol.*, Vol. 30, p. 922, Pl. 1, opp. p. 90.

[31] Elevation taken from *Times Atlas*, Pl. xcvi.

[32] A. Wegener, *The Origin of Continents and Oceans*, translated from the third German edition by J. G. A. Skerl; E. P. Dutton & Co., New York, 1924, p. 181. Wegener's book is an example of reasoning based on many such statements which, at least in the unqualified form in which they appear, are incorrect or at least liable to be misunderstood. Compare, by way of contrast, the impartial description of deep-sea troughs in A. Supan's *Grundzüge der physischen Erdkunde*, Leipzig, 1911, p. 268, or O. Krümmel, *Handbuch der Ozeanographie*, Vol. I, 1907, pp. 122-7.


60°
ATLANTIC
OCEAN
20°
BROWNSON TROUGH
4662
4000
3000
2000
1000
Anegada
Anegada Trough
Sombrero
Culebra
Virgin Is.
PORTO RICO
Vieques
St. Croix
Anguilla
St. Martin
St. Bartholomew
Saba
Saba Bank
Barbuda
Nevis
Antigua
Montserrat
GUADELOUPE
Marie Galante
Aves
DOMINICA
MARTINIQUE
St. Lucia
St. Vincent
Barbados
2844
Grenadines
Grenada
Blanquilla
Los Roques
Tobago
Margarita
Tortuga
TRINIDAD
10°
VENEZUELA
Folds formed at close of Paleozoic time
Folds formed at close of Cretaceous and at close of Eocene time
Folds formed during and after Miocene time
Island Arcs
Volcano

of these islands. It turns away abruptly in a right-angle bend, swinging against the southwest side of Bougainville Island of the Solomon Islands, leaving the northern half of the arc of the Bismarck Archipelago without a foredeep. The deep on the inside of the sharp arc of islands that curves around the east end of the Banda Sea, and the string of deeps that fringe the Andes from Valparaiso to Callao, must be called "backdeeps."[33] If we wanted to be consistent, such deeps as those found in the Bartlett Trough should be called "internal" deeps. Through the relatively shallow water of the "Windward Passage," the Bartlett Trough connects with the western continuation of the Brownson Trough which must be called a foredeep. Here, then, we see a chain of deeps intersecting a chain of islands. If such words as "foredeep" had no genetic implications this comment would be unnecessary. But Suess created the term "foredeep" expressly to designate depressions of the foreland caused by the weight of an overriding mountain fold.[34] A well coined descriptive term with a genetic implication quickly biases the mind and dulls its sensitiveness to reality. The history of tectonics and of physiography offers many cases to the point. Form and genesis can be comprised in one name without danger only where the specifically recognizable form of a structural or topographic feature is both necessary and sufficient to demonstrate the process by which it came into existence. Few writers have taken pains in the past to define accurately the specific characters of form or to prove its necessary and sufficient connection with the origin assigned to it.

Crustal Folds. Since "welts" and "furrows" are closely associated on the face of the earth, it will be convenient to use the more general term "crustal folds" for them.[35] The corresponding word "Grossfalten" has been in use here and there in German literature, but without satisfactory definition. Abendanon[36] applied it to larger upward deformations of all kinds and shapes with a definite implication of fault mechanics. More recently, Walther Penck proposed to restrict the

[33] W. H. Hobbs, *Earth Evolution and Its Facial Expression*, Macmillan Co., New York, 1921, p. 117.

[34] E. Suess-DeMargerie, *La Face de la Terre*, Vol. III, p. 1012.

[35] Even where fractures dominate their configuration near the surface, the term will be found useful not in spite of this broad and loose definition, but because of it. The different structural types will be introduced in later chapters.

[36] E. C. Abendanon, *Die Grossfalten der Erdrinde*, Leiden, 1914.

word "Grossfalten" to "crustal folds" somewhat in the sense of the "welts" and "furrows" of this book.[37]

Accepting the few illustrations given in the discussion of the fourth law, we can derive from them directly two further laws of considerable importance.

Law 6. "Welts" and "furrows" similar in form and dimensions exist at the level of the ocean bottoms as well as on the continental platforms.

It is true that the examples quoted above are not alike in dimensions. They were chosen chiefly because of their prominence in current geological discussions. Examples on smaller or larger scales are not difficult to find but will not be quoted here for lack of space.

This law seems to justify the first of a series of interpretative conclusions which we shall list and number separately as "opinions."

Opinion 1. The origin of "welts" and "furrows" is independent of the elevation of the earth's crust; it is especially independent of the distinction of the two dominant levels, the ocean bottoms and the continental platforms.

Elevation of crustal folds varies along strike.

Law 7. In modern "welts" and "furrows," the relative elevations of points varies greatly along the strike, giving rise to deeper hollows in the "furrows" and to higher groups of mountain peaks separated by sags in the "welts."

Like some of the others here set forth, this law seems almost a commonplace. Every orographical and bathymetrical map bears it out. A longitudinal section of any deep-sea trough, of any long drawn-out folded range of mountains is a sinuous line, with pronounced local sags and upward bulges. Yet when stretched rubber is coated with paraffin and then allowed to contract, or layers of mixed beeswax and plaster of Paris are compressed with the intention of reproducing the major structural forms of the earth's surface, we find it difficult to reproduce this part of the pattern. This may seem an undue emphasis

[37] See Walther Penck, *Die tektonischen Grundzüge Westkleinasiens*, Stuttgart, 1918; "Der Südrand der Puna de Atacama," *Ab. Sächs. Akad. Wiss., Math. Phys. Kl.*, Vol. 37, Leipzig, 1920. In "Die Morphologische Analyse." W. Penck, 1924, *Geographische Abhandlungen*, 2. Reihe, Heft 2, Stuttgart, we read: ". . . Ketten . . . und . . . Längsfurchen das Ergebnis einer welligen Verbiegung . . . der in bestimmten Räumen eine periphere, offenbar abgescherte Krustenschale unterworfen war und ist. Die Ketten sind in ihrem Wesen Antiklinen, die Senken Synklinen. Grossfaltung wurde der Vorgang genannt."

on a purely accidental feature which might be accounted for by local variations in the physical properties of the crust. It may be from the standpoint of the mechanics involved. However, we are here concerned merely with the fact of form. The local hollows in the deeps exist without evidence of an external force which brought them down; and the eminences along mountain ranges exist in most places without tangible evidence of a local force which caused their excessive rise. Although we know this, we feel the urgent need to appeal to "cross-folding" whenever we focus our attention on the presence of high points along the longitudinal section of a mountain range. Similarly we look for a local source of excessive sediment to account for an extraordinary depression in the floor of an older sedimentary trough. We must force ourselves to remember that it is "natural" for points along a "furrow" to sink more rapidly and more consistently than others and therefore to collect a greater thickness of sediments.

3. "Geosynclines" and "Mobile Belts"

Geosynclines.

Law 8. Laws 1 to 7 have been valid throughout the geological past as far as can be judged from available records.

Laws 1 to 7 are based on conditions now existing on the earth's surface. The evidence of their validity in the more remote past, especially of laws 4 to 7, we find in observations which may be generalized so as to take the form of corollaries to the eighth law.

(a) As early as 1857 Hall[88] emphasized for the Appalachian region what has since proved to be a general law, viz., that **intensely folded sediments are several times thicker than the formations of the same age in undisturbed regions.**

(b) The introduction of paleogeographic maps led to a broader recognition of the fact that at least since the beginning of post-Algonkian time the regions of **excessively thick sediments form relatively narrow, elongated belts.**

Using the Appalachian belt of paleozoic folds as prototype, Dana introduced the term "geosyncline" for a depression of the earth's

[88] Address before the American Association at Montreal, not published until 1883 under the title, "Contributions to the Geological History of the American Continent," *Proc. Am. Assoc. Adv. Sci.*, Vol. 31, 1883, pp. 29-69. See J. M. Clarke, *James Hall, of Albany, Geologist and Paleontologist*, 1921, p. 225.

crust which has received sediments of excessive thickness.[39] Later writers have proposed to add further special qualifications to the use of this term and to attach to it specific mechanical conceptions. Suess considered the resulting bias sufficient reason to omit the term entirely in the later parts of his work. He expresses regret at having at first employed the term in his *Face of the Earth.*[40] The writer is convinced that at least among American geologists the term can be retained to advantage in Dana's original sense. As a downward fold of the crust, in contrast to folds in sediments, it becomes a synonym for the neutral word "furrow" used in these pages. But it focuses the attention on the sedimentary contents and in that sense does not duplicate the latter word. Similarly we speak of the piedmont "plateau" when we view its topographic expression, while we call it a "peneplain" when we focus attention on the amount of rock removed from its present surface.

The elongated, furrow-like character of geosynclines is not a part of the concept as defined but constitutes an independent fact revealed by a world-wide study of geosynclines. In the paleogeographic maps of Vol. II of Émile Haug's *Traité de Géologie* (1908-1911), geosynclines have appeared graphically differentiated from other areas of sedimentation. On Haug's maps it is the nature of the marine sediments and the completeness of the stratigraphic record, not the thickness itself, which defines the geosynclinal areas.

The first systematic representation of geosynclines on the strictly impartial basis of actual thickness of sediments was given by Professor Schuchert[41] in his presidential address before the Geological Society of America in 1922, and published fifty years after Dana coined the term geosyncline. One of Schuchert's maps is here reproduced in Fig. 3 (map 5, p. 217 of original). To the legend of this

[39] J. D. Dana, "On Some Results of the Earth's Contraction from Cooling," *Am. Jour. Sci.*, 3rd ser., Vol. 5, 1873, p. 430. In Vol. 6, 1873, p. 717, Dana summarizes his use of this and allied terms as follows: "There are two kinds of monogenetic ranges —those that are geanticlinals, or anticlinoria, like the region of the Cincinnati uplift; and those that were the result of a slowly progressing geosynclinal, and consequently a very thick accumulation in the trough of sedimentary beds, ending in an epoch of displacements and solidification, and often of metamorphism of the sedimentary beds, as in the case of the Alleghanies and other *synclinoria.*"

[40] *The Face of the Earth*, Vol. IV, 1909, p. 627 (or *La Face de la Terre*, Vol. III, p. 1618).

[41] Ch. Schuchert, "Sites and Nature of the North American Geosynclines," *Bull. Geol. Soc. America*, Vol. 34, 1923, pp. 151-230.

map a few figures have been added, taken from the accompanying paper to bring out the magnitudes involved.

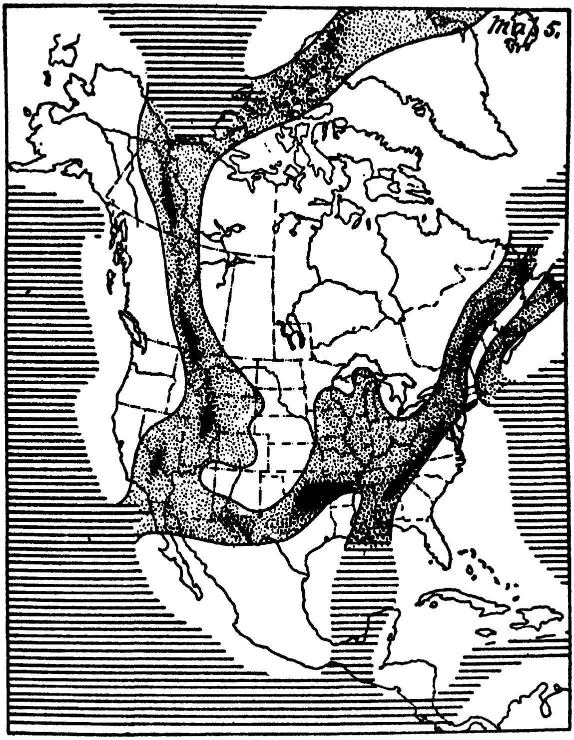


Fig. 3. Paleogeographic map of North America for Upper Cambrian and Lower Ordovician (Canadian) time.
(Ch. Schuchert, 1923)

The coarse stippling indicates thicker sediments. The geosynclinal belts along which the sediments reach exceptional thickness are indicated in black.

(In round figures, Cambrian and Ordovician sediments combined measure 15,000 feet in northeastern Tennessee and southwestern Virginia; 22,800 feet in northeastern Alabama; Upper Cambrian to Middle Ordovician strata, 7,000 feet in Arbuckle Mountains of eastern Oklahoma.)

Clastics of geosynclines.

(c) The largest part of the terrigenous sediments that fill the geosynclines was derived from highlands closely adjoining them and not from the large continental lowlands of the "swells."

(d) Coarse waterlaid sediments, conglomerates, breccias, and arkoses, that indicate rapid erosion of rapidly risen highlands, are practically limited to geosynclinal belts (tillites of continental glacial origin excluded).

The last two generalizations prove that in the past, as at the present, "welts" stood closely associated with furrows and did not exist regionally separated from them. The contents of (c) have become a commonplace of stratigraphic teaching in the United States, so far as the major geosynclines are concerned. The Algonkian-Cambrian geosyncline of the northern Rocky Mountains, as shown in Daly's diagrammatic section, may serve to illustrate the conditions observed in the United States. (Fig. 4.)[42] A fine European illustration is found

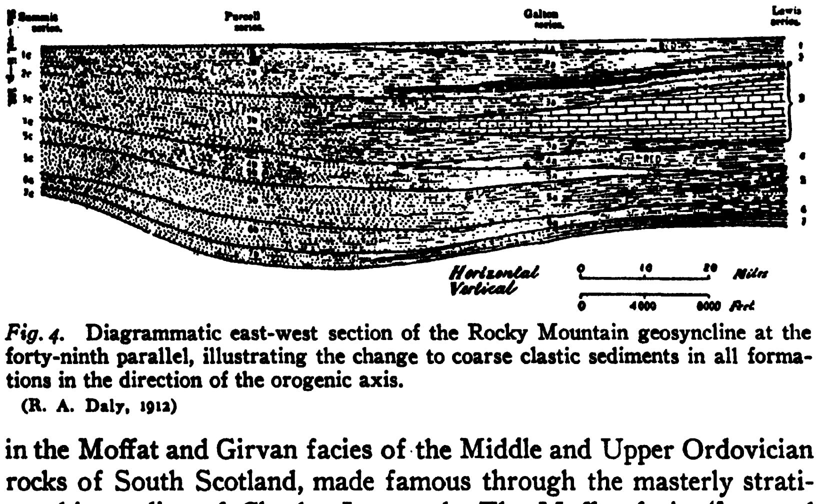


Fig. 4. Diagrammatic east-west section of the Rocky Mountain geosyncline at the forty-ninth parallel, illustrating the change to coarse clastic sediments in all formations in the direction of the orogenic axis.
(R. A. Daly, 1912)

in the Moffat and Girvan facies of the Middle and Upper Ordovician rocks of South Scotland, made famous through the masterly stratigraphic studies of Charles Lapworth. The Moffat facies,[43] named after the type locality in Moffat Valley, some 25 miles northeast of Dumfries, consists of graptolite shales, partly in the form of pyritiferous black shales, with radiolarian cherts. The total thickness of the post-Sciddavian Ordovician is less than 200 feet. To the westward, some 55 miles, the facies changes to that of the Girvan[44] district, on

[42] Reproduced from R. A. Daly, "Geology of the North American Cordillera at the Forty-ninth Parallel," *Canada Geol. Survey, Memoir 38*, 1912, Pl. 21, opp. p. 168.

[43] Charles Lapworth, "The Moffat Series," *Quart. Jour. Geol. Soc.*, Vol. 34, 1878, pp. 240-346, esp. p. 250.

[44] *idem*, "The Girvan Succession," *Quart. Jour. Geol. Soc.*, Vol. 38, 1882, pp. 537-666, esp. p. 661.

the southeast shore of the Firth of Clyde. Here the same series measures about 3,600 feet in thickness and consists largely of coarse clastics. Among these are the "Kirkland conglomerate," 100 feet thick, a boulder conglomerate with calcareous matrix of purple, red, or white color; and the "Benan Conglomerate," 500 feet thick, a "coarse boulder conglomerate," with sandy or gritty matrix of green or gray color. The significance of this change of facies, for our purposes, lies in the conspicuous increase of coarse clastics as the Caledonian land barrier[45] is approached. Here again the highland, the source of the clastics, is a part of the geosynclinal belt, a typical "welt" adjoining the "furrow" that received the 3,600 feet of largely marine strata.

The maps that accompany Lapworth's papers illustrate the highly complicated structure of the Scottish Mountains which, like that of the late Paleozoic ranges, and especially the Alpine system, early led to studies of facies. In the Gordian knot of Alpine structure the question of changes of facies is inextricably involved. One of the most effective proofs of the correctness of the *decken* (*nappe*) theory arose from the classical studies of Arnold Heim[46] in the northern ranges of the Eastern Swiss Alps. Fig. 5 reproduces a diagram[47] which shows the thickness and facies development of the Cretaceous rocks in two overthrust *decken* above the autochthonous Cretaceous. If the rocks of these *decken* had been deposited essentially at the place where they are found now, the three units (plus a small fourth one not included in Fig. 5) would have lain side by side as shown in Section *A-A.* of Fig. 6. This grouping is, of course, quite impossible. If, on the other hand, the *decken* are moved back to the south, the direction from which their structure indicates them to have been derived, the higher being moved farther south than the lower one, the result is the orderly sequence shown in Section *B-B* of Fig. 6. Arnold Heim's analysis is not limited to profiles. On a map he showed

[45] See, e.g., paleogeographic map in A. Born, "Das Ordovicium," in Wilh. Solomon, *Grundzüge der Geologie*, Vol. II, p. 131.

[46] Arnold Heim, "Monographie der Churfürsten-Mattstockgruppe," *Beitr. z. Geologie d. Schweiz,* N.F., Lieferung 20, 1910-1917. See also Arnold Heim, "Ueber Abwicklung und Facieszusammenhänge in den Decken der nördlichen Schweizeralpen," *Vierteljahrsschrift der Naturf. Ges. Zürich,* 1916.

[47] Reproduced from Alb. Heim, *Geologie der Schweiz,* Vol. II, 1921, Figs. 12 and 13, pp. 25-6.

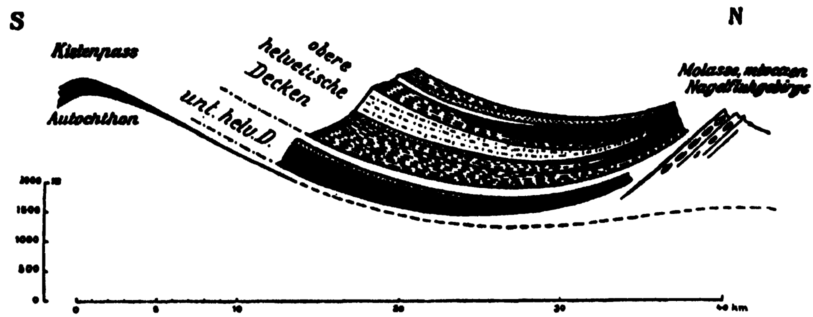


Fig. 5. Diagrammatic section across the upper and lower Helvetic *decken* of the northern Swiss Alps, thrust from the south across the sedimentary mantle of the autochthonous Aar massif onto the Miocene foreland (Molasse). Designed to show the variation in thickness and facies in the Cretaceous sediments of the two *decken*. (Compare with Fig. 6.)

Black = (shallow water) "Urgon" limestone facies; dashed = calcareous shales; stippled = (deeper water) bathyal facies.

(After Arnold Heim, reproduced from Alb. Heim, *Geologie der Schweiz*, 1921, by permission of Bernhard Tauchnitz A. G.)

the distribution of facies by what he calls "isopic lines" ("Isopen"), lines connecting points of identical facies. Similarly the distribution of thicknesses is represented by "isometric lines," or lines connecting points of equal thickness of sediments (= isopachs).

We are here not concerned with the far-reaching structural implications of these studies. We note the increase of clastic materials away from the stable land to the north and toward the unstable region of rising "welts" to the south. The presence of rising "embryonic" Alpine chains[48] in the waters of the Mesozoic seas of the Alpine region is indicated by gaps in the sedimentary series and especially by the presence of conspicuous conglomerates and breccias. In the Rhaetikon Mountains, on the Austrian-Swiss border, east of the Rhine, for instance, conglomerates and breccias are found in the Lower and Upper Jurassic and also in the Cretaceous. The Upper Jurassic breccia of Falkniss Mountain shows poorly rounded fragments of variable size (up to three meters diameter) derived from various intrusive and metamorphic rocks and (fewer) dolomites, cherts, and sandstones, bound in a light gray limestone matrix rich in

[48] See E. Argand, "L'arc des Alpes Occidentales," *Eclogae Geol. Helvet.*, Vol. 14, 1916; R. Staub, "Uber Faziesverteilung und Orogenese in den südöstl. Schweizer Alpen," *Beitr. z. Geologie d. Schweiz*, Vol. 46, 1917.

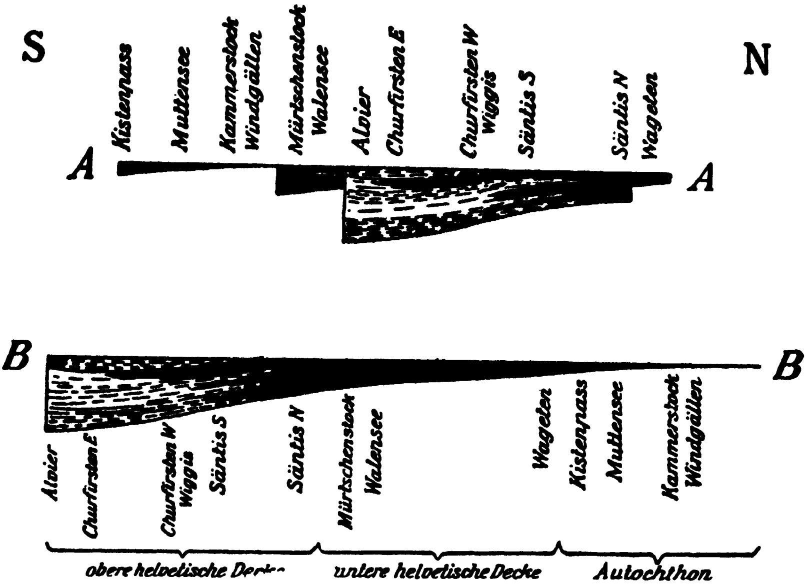


Fig. 6. Diagrammatic sections showing the relations of thickness and facies in the upper and lower Helvetic *decken* when laid end to end. *A*, arranged with the autochthonous sediments farthest south, as they are seen today. *B*, restored to the original sequence, with the uppermost *decke* farthest south.

Symbols the same as in Fig. 5.

(After Arnold Heim, reproduced from Alb. Heim, *Geologie der Schweiz*, 1921, by permission of Bernhard Tauchnitz A. G.)

foraminifera with remains of sponges and corals. On the basis of careful study Trümpy concluded that the rising range from which these fragments were derived never stood far above the ocean surface and was largely a submarine ridge destroyed through wave erosion.[49] The largest development of similar conglomerates and sedimentary breccias in the Alps is found in one of the *decken* of the "Préalpes," south and east of Lake Geneva. Here both the Lower and the Upper Jurassic contain huge masses of breccias carrying fragments of Carboniferous schists, Triassic quartzites, slates and dolomites, and even limestones of Lower Jurassic age. The Lower Jurassic breccia alone reaches thicknesses from 1,600 to over 5,000 feet.[50] This so-called

[49] Daniel Trümpy, "Geol. Untersuchungen im Westl. Rhaetikon," *Beitr. z. Geologie d. Schweiz*, 1916 (quoted from Alb. Heim, *Geologie der Schweiz*, Vol. II, p. 766-7).

[50] According to Lugeon, quoted from Alb. Heim, *Geologie der Schweiz*, Vol. II, 2, p. 610.

"Breccien-Decke" has been thrust far northward. Its original position must be sought in the heart of the present Alpine chain, where remnants of similar breccias occur, especially in the French Alps.

Involved in immensely complicated structure and preserved only in patches widely separated by thrusting and subsequent erosion, these marine conglomerates and breccias of the ancestral Alps have not until recently attracted the attention they deserve. Such thicknesses, as quoted above from the Chablais region south of Lake Geneva, render them quite comparable to the conspicuous conglomerates of the Upper Oligocene and Miocene that accompany the north margin of the Alps.[51] They are known as the "Nagelfluh" facies of the marine and freshwater sediments ("Molasse") of the Tertiary Alpine foreland. Anyone who has seen the nearly vertical south wall, some 800 feet high, of Mt. Rigi on the Lake of the Four Cantons in Switzerland, cannot have failed to be impressed by them. In the vicinity of the Rigi they reach a thickness of nearly 10,000 feet.[52] The preponderance of quartz and cherts, the foreign source of many other materials, and especially the high degree of rounding of most pebbles, so close to the (overthrust) front of the Alpine ranges, involve fundamental questions of the rise of mountain ranges. The summary of numerous detailed investigations on the "Nagelfluh" given by Albert Heim in Vol. I of his monumental *Geologie der Schweiz* (pp. 43-72) is stimulating reading. Fig. 7 reproduces a diagram[53] which serves to illustrate the preponderant rôle played by the rising Alpine chains in furnishing coarse clastics to that part of the Tertiary basin that lies between the Vosges Mountains and Black Forest on the north and the north front of the Swiss Alps.

American readers will compare this with the locally very coarse conglomerates in front of the Rocky Mountains, such as the Paleocene Arapahoe and Denver formations,[54] or the Neocene Monument[54] and Castle Rock conglomerates.[55] The last two represent the

[51] For a map showing the distribution of these conglomerates in Switzerland, see Pl. IV, opp. p. 48, in Alb. Heim, *Geologie der Schweiz*, Vol. I, 1919.

[52] Albert Heim, *op. cit.*, Vol. I, p. 44.

[53] Reproduced from Alb. Heim, *op. cit.*, Vol. I, 1919, p. 65.

[54] See, e.g., G. H. Eldridge, "Post-Laramie and Tertiary Geology," in *U.S. Geol. Survey, Mon. 27*, "Geology of the Denver Basin," 1896.

[55] See, e.g., G. B. Richardson, "Castle Rock Folio," *U.S. Geol. Survey, Folio No. 198*, p. 9.

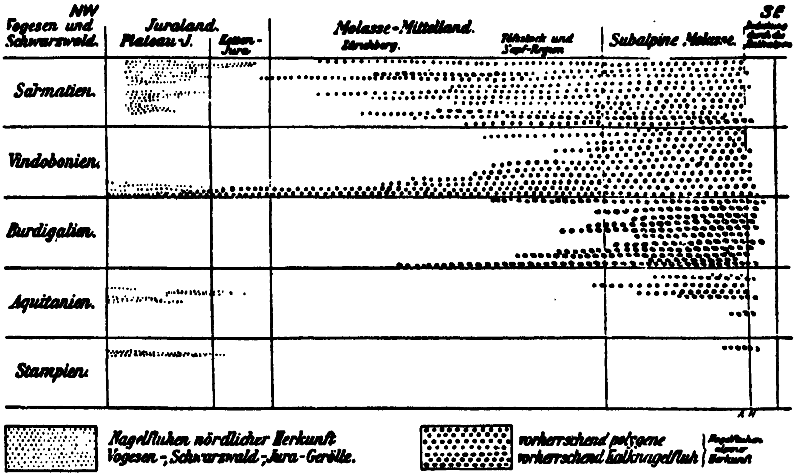


Fig. 7. Diagram showing the horizontal and vertical distribution of conglomerates ("Nagelfluhen") in the Miocene sediments (Molasse) of the foreland of the Swiss Alps.

Small circles = pebbles derived largely from calcareous sediments which mantled the crystalline core of the Alps.

Coarse stipples = conglomerate rich in crystalline rocks derived from the Alps.

Fine stipples = pebbles derived from swells lying north of the Miocene foreland of the Alps.

(Alb. Heim, *Geologie der Schweiz*, 1919; reproduced by permission of Bernhard Tauchnitz A. G.)

coarse piedmont phases of the widespread clastics of the Great Plains Tertiary.

The coarse marginal conglomerates of the Triassic red beds of the eastern United States may be mentioned as still another facial expression of such coarse sediments[56] on the margins of rising "welts." Here the conspicuous change in the composition of the pebbles and boulders that make up the conglomerate called the attention of all

[56] See, e.g., Arthur Keith, "Geology of the Catoctin Belt," *U.S. Geol. Survey, Eighteenth Ann. Rept.*, Vol. II, pp. 346-52. H. B. Kümmel, "The Newark System," *New Jersey Geol. Survey, Ann. Rept. for 1897 (1898)*, pp. 52-8; H. B. Kümmel, "The Extension of the Newark System of Rocks," *ibid., Ann. Rept. for 1898 (1899)*, pp. 49-50; (also a summary, "The Newark Rocks," *Jour. Geol.*, Vol. 7, 1899, pp. 32-5); B. K. Emerson, "Geology of Old Hampshire County, Mass.," *U.S. Geol. Survey, Mon. 29*, 1898, pp. 351-79; W. M. Davis, "The Triassic Formation of Connecticut," *U.S. Geol. Survey, Eighteenth Ann. Rept.*, Part II, 1897, pp. 29-34; J. Barrell, "Central Connecticut in the Geologic Past," *Connecticut Geol. Survey, Bull. 33*, 1915.

investigators to the question of the source of the coarser clastics. The distinction of "limestone conglomerate" and "quartzite conglomerate," the latter more or less rich in pebbles of crystalline rock, corresponds directly to the "Kalknagelfluh" and "Bunte Nagelfluh" of the Swiss Molasse.

"Mobile belts." The most general aspect of the contents of the first seven laws is that of relatively narrow zones to which "furrows" and "welts" are confined in contrast to the broad expanses of earth surface between them. Gilbert introduced the term "orogenesis" for the processes that create such zones in contrast to the milder and broader changes of level that constitute "epeirogenesis." The liability to greater vertical movement may be spoken of as greater "mobility." In this sense we are justified in speaking of these "orogenic belts" also as the "mobile belts" of the earth's surface.

Opinion 2. The zones of crustal folds, of "welts" and "furrows," are the outcrops at the surface of relatively narrow sections of the earth's crust which display greater mobility than the remainder of the crust.

In the question, why they should be more mobile, lies the central problem of earth deformation.

CHAPTER II

ISOSTASY

"We are forced to confess that our wonder has been more excited than our reasoning powers."
James Hall, in presidential address, 1857.

1. Isostatic Equilibrium

The Law. In the first chapter we concerned ourselves only with the general surficial aspect of the earth's belts of large deformation. As we turn to laws that cover more specific qualities of crustal deformation, the fundamental questions of causal relations force themselves more and more to our attention. It is desirable that we present the laws that follow in such an order that the opinions drawn from them lead to a consistently enlarging critical view of possible causal relations. Even in the first chapter we had occasion to refer to a concept that has lately colored more or less intensely the thoughts of all geologists. We cannot profitably go farther in our account of geological realities without first setting forth a law derived from geodetic observations, the law of isostatic compensation.

Law 9. In an outer shell of limited thickness on the earth, columns of unit area possess approximately the same mass, regardless of the elevation of their surfaces; that is, their densities vary inversely as their heights above a standard surface which lies between fifty and one hundred kilometers below sea level.

This is the law of isostatic compensation. It states that each gain or loss of height in a column of this outer shell is neutralized, "compensated," by a corresponding loss or gain in density. In other words, for any column of the shell the product volume × density is (virtually) constant.

The proof of the essential truth of this law lies in the power it gives to compute for any point on the earth both the intensity of gravity and its direction, that is, its local deviation from the normal vertical.

Computed and observed values of gravity. The computation of the value of gravity for any station on the earth's surface may serve as illustration. It involves a number of steps. First, the computation

is made for a hypothetical earth of uniform density having the shape of a mathematically simple body of dimensions corresponding as nearly as possible with the surface of the sea. The exact determination of this ideal shape of the earth as a whole, the basic task of geodesy, has not been achieved as yet. The shape is that of either a biaxial or triaxial ellipsoid.

The deviation from the form of a sphere and the rotation of this ideal earth cause gravity to vary from point to point, with latitude only, if it is biaxial; with latitude and longitude, if it is triaxial. Corresponding equations give the value of gravity for any point of given latitude and longitude.

The value of gravity thus computed for a point on this ideal earth differs from that found at a corresponding point on the actual earth because the earth is neither a simple spheroid nor of uniform density. In order to approximate the real conditions, terms must be added to the fundamental equation, so-called "corrections."

While retaining the initial assumption of uniform density, terms may be added correcting for the effect of the earth's topographic irregularities. This effect is complex. First, for all stations which do not lie at sea level, mere distance above or below the level of the ideal ellipsoid (supposed to coincide with sea level) alters the value of gravity. Second, this value is influenced by the mass of the rock that lies between the stations and the ellipsoid or the absence of such rock in oceanic stations. Finally, the value of gravity is affected by all excesses and deficiencies of mass due to all topographic irregularities of the whole earth's surface, that is, by the algebraic sum of the components of the gravitational effect of all these excesses and deficiencies of mass.

When a term is added to the fundamental equation which covers the first item only, that is, when the mass effect of topography is neglected, gravity values are obtained which, for inland stations, are too low. This is the so-called "free-air" correction.

For purposes of comparison, the computed values of gravity, (g_o) are subtracted from those obtained by measurement (g_m). The resulting difference ($g_m - g_o$) is called the "gravity anomaly." In the first column of Table I the gravity anomalies are listed for a number of stations, as obtained by the "free-air" correction. They are all positive, that is, the computed values fall short of those observed.

The correction for the total mass effect of all topography involves such difficulties that it can be achieved only approximately by means of simplifying assumptions. A first approximation was given by Bouguer who proposed to neglect the curvature of the earth's surface: "The topography being treated as if it were standing on a plane of indefinite extent."[1]

TABLE I

Comparison of gravity anomalies obtained by the use of the "free-air," Bouguer, and Hayford equations.

STATION	HEIGHT IN FEET	GRAVITY ANOMALY (g_m-g_o) "FREE-AIR"	BOUGUER	HAYFORD
*America**				
Arizona	7,187	+ 43	—162	+ 9
Pikes Peak	14,159	+216	—214	+29
Wyoming	7,873	+ 44	—208	+ 6
Gallup	6,565	+ 9	—211	— 5
California	3,458	+ 13	—103	— 2
Asia†				
Mussooree	6,924	+ 84	—123	+53
Sandakphu	11,766	+189	—155	+48
Quetta	5,520	+ 31	—153	+ 7
Ootacamund	7,395	+195	— 46	+12
More (Tibet)	15,427	+100	—419	+18
*Europe**				
Stilfserjoch (Austria)	9,108	+142	—141	—18
Schneekoppe (Germany)	5,296	+139	— 26	+21
Gornergrat (Switzerland)	9,952	+218	— 92	+45
St. Bernard (Switzerland)	8,260	+141	—113	+ 2
Franzenhöhe (Austria)	7,220	+ 73	—182	—22

* Wm. Bowie, "Investigations of Gravity and Isostasy," *U.S. Coast and Geodetic Survey, Spec. Pub. 40,* 1917.

For the United States, see also *Spec. Pub. 10,* 1912; *12,* 1914; *99,* 1924. The first by J. F. Hayford and Wm. Bowie, the others by Wm. Bowie.

† H. Couchman, *Trigon. Survey of India, Prof. Paper 15,* 1915.

The whole table is quoted from Sir S. Burrard, "A Brief Review of the Evidence upon which the Theory of Isostasy Has Been Based," *Geog. Jour.*, Vol. 56, 1920, p. 49.

The second column of Table I shows the anomalies resulting from gravity values computed with Bouguer's equation. Here all the computed values are larger than the observed ones, making all anomalies

[1] J. F. Hayford and Wm. Bowie, "The Effect of Topography and Isostatic Compensation upon the Intensity of Gravity," *U.S. Coast and Geodetic Survey, Spec. Pub. No. 10,* 1912, p. 75. Bouguer's figures do not, therefore, indicate correctly the deficiencies and excesses of mass, as many European geologists seem to assume. (See, e.g., A. Born, *Isostasie und Schweremessung: Ihre Bedeutung für geologische Vorgänge,* Berlin, 1923.)

negative. The difference is far greater than the neglect of the curvature of the water surface warrants. The only possible conclusion is that the topographic elevations do not wholly represent extra masses. Something corresponding to law 9 must be true.[2]

It was to be expected that equations which are based on the initial assumption of uniform density would not yield good results. But it could not be foreseen that there would be any uniform relation between mass and elevation above sea level. In order to introduce this relation into the computation of gravity, assumptions must be made concerning the corresponding density variations. In order to be amenable to mathematical treatment, the assumed scheme of density variation must be simple.

Two types of density distribution have been suggested and evaluated mathematically. The simpler of the two assumes that density varies in some way inversely with elevation. Hayford created equations based on this assumption. In his equations, the mass of the column beneath each topographic feature, measured from sea level down to an arbitrarily chosen depth, is assumed to be deficient or in excess by an amount exactly equal to that represented by the topographic feature which rises above it or falls below it. The deficiency or excess is assumed to be distributed uniformly through the column, for purposes of mathematical treatment. This is called "isostatic compensation." The thickness of the column through which this deficiency or excess of mass is distributed mathematically, is called the "zone of compensation," its base the "depth of compensation."

The equations formed by Hayford, which include a term for the isostatic compensation, were used by Bowie for determining the depth

[2] Recently the Viennese geodesist Hopfner tried to show that the "deficiency of mass" in continents is only apparent and is merely the mathematical consequence of the upward deflection of all equipotential surfaces within masses which project above sea level. The effect on which Hopfner bases his arguments has long been known and has been discussed by Helmert, Bowie, and others. While qualitatively true, it is quantitatively inadequate to explain the anomalies actually observed. See F. Hopfner, "Isostasie und Hauptträgheitsachsen," *Gerlands Beitr. z. Geophysik*, Vol. 21, 1929; "Zur Begründung der Lehre von der Isostasie," *ibid.*, Vol. 22, 1929; "Die Lehre von der Isostasie und Dreiachsigkeit der Erde," *Petermanns Mitt.*, Vol. 76, pp. 10-14. For refutations of Hopfner's views see W. D. Lambert, "Brun's Term and the Mathematical Expression for the Gravity Anomaly," *Gerlands Beitr. z. Geophysik*, Vol. 21, 1929, Heft 4; W. Heiskanen, "Isostasie und Erddimensionen," *Petermanns Mitt.*, Vol. 77, 1931, pp. 122-7. (The writer has read only the papers by Hopfner and Heiskanen published in *Petermanns Mitt.*)

of compensation from the gravity data in the United States. He found a depth of sixty kilometers when all stations were used and ninety-five kilometers when the more decisive ones were used. Bowie's value was so close to the one derived by Hayford from deflection data that the mean of the two, or ninety-six kilometers, was accepted as being the most probable one.[3]

Hayford's equations have been applied to gravity data from other continents.[4] The third column of Table I shows the results. Hayford's equations have permitted the value of gravity to be computed in advance of observation with an error of only one-fourth to one-fifth or less of that resulting from the "free-air" and Bouguer equations.

But equally successful computations have been made on the basis of an entirely different assumption concerning the mass distribution in the outermost shell of the earth. This was suggested by the presence of two dominant levels on the earth, the mean levels of the continents and of the ocean bottoms. Corresponding to these two levels, the outermost shell of the earth is assumed to consist essentially of two materials of fixed density, an upper, lighter, and a lower, heavier material (say, for instance, granite and basalt). The lighter material lies on top and forms the continents. The variations in the mean density of different columns of the earth's crust are assumed to result from variations in the thickness of the outer, lighter layer.

The equations and tables for the computation of gravity on this basis were recently created by the Finnish geodesist Heiskanen.[5] Like

[3] Wm. Bowie, "Investigations of Gravity and Isostasy," *U.S. Coast and Geodetic Survey, Spec. Pub. No. 40*, 1917.

[4] A. H. Miller, "Gravity Results in the Mackenzie Basin," *Jour. Roy. Astron. Soc. Canada*, Nov.-Dec., 1923; also "Gravity in Northwestern Canada," *Pub. Dominion Observatory*, Vol. 8, No. 6, Ottawa, 1924; Wm. Bowie, "Isostasy in Western Siberia," *Am. Jour. Sci.*, 5th ser., Vol. 21, 1926; W. Heiskanen, "Untersuchungen über Schwerkraft und Isostasie," *Pub. 4, Finnish Geodetic Institute*; S. Huelin, "La Reducción isostatica de nuestras estaciones de gravidad," *Memorias del Instituto Geographico y Catastral*, Madrid, Vol. 15, 1926, pp. 1-18 (reviewed by Wm. Bowie in *Am. Jour. Sci.*, 5th ser., 1926); Wm. Bowie, "Isostasy in the Southern Pacific," *Jour. Washington Acad. Sci.*, Vol. 15, 1925, pp. 445-50; "Isostatic Reductions, by the U.S. Coast and Geodetic Survey, of the Results of the Pendulum Observations at Sea Made in 1923 between Holland and Java," *Pub. Dutch Geodetic Committee*, 1926.

[5] W. Heiskanen, "Untersuchungen über Schwerkraft und Isostasie," *Pub. 4, Finnish Geodetic Institute*, Helsingfors, 1924. (Not seen by the present writer. Contents quoted from W. Lambert's review in *Am. Jour. Sci.*, 5th ser., Vol. 10, 1925. pp. 82-9.)

Hayford, Heiskanen computed gravity for different arbitrary values of the unknown variables in his equations, the average thickness of the crust and the difference in the densities of crust and magma. Geologists who have been quick in drawing far-reaching conclusions from the sign and magnitude of gravity anomalies should note that for such prominent mountain regions as the Alps and the Caucasus mountains Heiskanen obtained results which are contrary to the current ideas based on a "too exclusive use of the Bouguer anomalies."[6] In general, the anomalies obtained by means of Heiskanen's equations are even slightly though not significantly smaller than those obtained by Hayford.

The success of both conflicting assumptions suggests that they share a crucial concept. This seems to be the idea that the compensation for excess mass is accomplished, at least on the average, within a definite "zone of compensation" of limited thickness. By both Hayford's and Heiskanen's equations, the thickness of the zone within which density differences seem to be effective is found to lie between 50 and 100 kilometers. This, then, seems sufficiently proven to justify being included in law 9.

By either method of computation, the geodesist approaches remarkably close to his goal, the accurate computation of gravity for any station on the earth. He is concerned primarily with approximating further the observed values of gravity. If the isostatic equilibrium were perfect everywhere and if the local distribution of densities were known, it should be possible to reduce all anomalies to zero. The question of the degree of perfection of isostasy is for this and other reasons the chief concern of the geodesist.

To the geologist, on the other hand, the realities back of the law of isostatic compensation constitute the fundamental problem. We shall take up first the question of the degree of perfection of the isostatic equilibrium and then that of the realities back of it.

2. The Degree of Perfection of Isostatic Equilibrium

Surface densities and gravity anomalies. In geodetic as in all modern measurements, the limits of error are carefully determined. They are found to be much smaller than the anomalies. If Hayford's or Heiskanen's equations embodied all factors that influence the actual

[6] W. D. Lambert's review of Heiskanen's work, *op. cit.*, p. 85.

value of gravity at a given station, the anomalies would be a direct measure of the departures from perfect isostatic equilibrium. Unfortunately, this is not the case. At least two factors are known that do not appear in the equations. One is a small systematic error introduced at the outset in the mathematical treatment of gravity.[7] A glance at the tables and maps in the publications of the U.S. Geodetic Survey shows at once that the distribution of the anomalies is essentially unsystematic. This error cannot, therefore, be responsible for more than an insignificant part of the anomalies.

The other factor is the effect of density differences in rock masses close to the station at which gravity is observed. Since gravitative attraction varies inversely as the square of the distance, a heavy rock mass immediately beneath a station will register an excess of gravity over that of surrounding crustal columns of equal elevation and equal mean density. Thus local concentrations of abnormal densities close to the surface and, in general, all vertical irregularities in density in columns of equal average density must have an important effect on the observed values of gravity.

The importance of materials near the surface was pointed out early by Gilbert.[8] It was discussed to a certain extent by Hayford and Bowie in their publication on gravity determinations.[9] It was considered in detail by Bowie[10] and was emphasized by Hobbs, Lane, Burrard, and others. Burrard, for instance, following the suggestion made by Bowie, attributed the high negative anomalies in the Himalayan region to the thickness of unconsolidated sediments in the Indo-Gangetic plain.[11]

Barrell discussed this effect elaborately in his *Strength of the Earth's Crust*. A systematic study of the relation of gravity anomalies to the density of surface rocks was given by David White in

[7] See footnote concerning Hopfner's criticism, p. 28.

[8] G. K. Gilbert, "Notes on the Gravity Determinations Reported by Mr. G. R. Putnam," *Bull. Philos. Soc. Washington*, Vol. 13, 1895, pp. 61-5.

[9] J. F. Hayford and Wm. Bowie, "The Effect of Topography and Isostatic Compensation upon the Intensity of Gravity," *U.S. Coast and Geodetic Survey, Spec. Pub. 10*, 1912, pp. 113-17.

[10] Wm. Bowie, "Investigations of Gravity and Isostasy," *U.S. Coast and Geodetic Survey, Spec. Pub. 40*, 1917.

[11] Sir S. G. Burrard, "Investigations of Isostasy in Himalayan and Neighboring Regions," *Trigon. Survey of India, Prof. Paper 17*, 1918. (Quoted from Wm. Bowie, *Isostasy*, 1927, pp. 81-2.)

his presidential address before the Geological Society of America in December 1923.[12] His studies leave no doubt about the existence of a definite correlation between large anomalies and large deviations from average density near the earth's surface.

If this effect could be incorporated into the Hayford or the Heiskanen equations, the anomalies would be decreased still further. Yet, quantitative tests show convincingly that the anomalies would not be wiped out by such additional correction. The remaining anomalies, then, would be due to actual departures from isostatic equilibrium. The magnitude of such departures would give a measure of the strength of the outermost shell of the earth and would, therefore, be of great interest to the geologist.

Gravity anomalies as a measure of the strength of the earth's crust. If isostatic compensation is not perfect, that is, if isostatic equilibrium is not complete, the crust must be able to bear an extra load or a deficiency of mass without yielding to the resulting stresses. The magnitude of the stresses depends on the thickness and horizontal extent of the excess mass. A judicial and statistical treatment of the gravity anomalies should give an idea of the limits within which the earth's crust can sustain a load.

Comparative tests have shown that all gravity anomalies are reduced to a minimum when the compensating effect is assumed to be limited to a column not extending far beyond the station. When the compensation is assumed to extend farther than one hundred miles from a station, the anomalies rise rapidly.[13] When different radii smaller than one hundred kilometers are assumed, the resulting anomalies do not differ significantly, so that for purposes of computation the assumption of a short radius is as good as that of a long one, provided it does not exceed much the one hundred kilometer limit.

American geodesists emphasize the slight evidence in favor of a small radius for columns in which isostatic equilibrium approaches perfection. They think it probable that a disk of rock material 3,000 feet in thickness and 18 miles in radius is essentially compensated.[14]

[12] David White, "Gravity Observations from the Standpoint of the Local Geology," *Bull. Geol. Soc. America*, Vol. 35, 1924, pp. 207-78.

[13] Wm. Bowie, *Isostasy*, 1927, pp. 63-4.

[14] *idem*, "Theory of Isostasy—A Geological Problem," *Bull. Geol. Soc. America*, Vol. 33, 1922, p. 280.

This would mean that the compensating effect is essentially localized beneath each point of the surface and compensation is nearly perfect.

Barrell has given a critical account of geological observations which indicate a considerably higher strength of the earth's crust. He gives weighty arguments to show that such bodies of rock as the deltas of the Nile and Niger rivers constitute real and present burdens sustained by the rigidity of the crust. If allowance is made for the sea water displaced by these deltas, their net weight corresponds to rock masses of 4,000 feet and 5,000 to 5,500 feet thickness, respectively. These masses are spread, with thinning margins, over areas corresponding to circles with radii measuring 175 kilometers and 250 kilometers, respectively.[15]

Recently Longwell[16] pointed out that the gravity anomalies obtained on the Mississippi delta indicate that much of the delta constitutes an extra load on the crust. The algebraic sum of the anomalies found for eight stations on the delta is almost zero (—0.005 dyne).[17] If the column beneath the delta were in isostatic equilibrium, the light, unconsolidated sediments of at least the upper part of the delta should register a strong negative anomaly for reasons elaborated above (pp. 31-2). If the delta constituted a local, essentially equidimensional body, the absence of such strong negative anomalies would mean that there is an excess of mass below, that is, the crust is not in equilibrium and that the delta constitutes an excess load. If, on the other hand, its shape approached that of a thin sheet of large horizontal dimensions, its differential effect on the value of gravity would be negligible. Since actually its shape lies between these two extremes, Longwell's argument, while not applying with full force, remains sufficiently significant to deserve attention.

Barrell also pointed to the apparent lack of compensating movements in broad areas which have suffered much denudation, such as the Mohawk, St. Lawrence, and Champlain valleys with respect to the Adirondacks, as evidence of relatively high crustal strength.

[15] J. Barrell, "The Strength of the Earth's Crust," *Jour. Geol.*, Vol. 22, 1914, pp. 36-48.

[16] C. R. Longwell, "Some Problems of Mountain Structure and Mountain History," *Am. Jour. Sci.*, 5th ser., Vol. 19, 1930, pp. 432-4.

[17] Not —0.007 dyne, as stated in *U.S. Coast and Geodetic Survey, Spec. Pub. 99*, p. 49, from which Longwell took the figure. (Correction given in letter from Dr. Bowie to the writer.)

As far as the surface area of blocks is concerned which are in isostatic equilibrium, these observations suggest that the larger limit indicated by the geodetic computations, that of a radius of 100 miles (160 kilometers) is nearer the truth, perhaps even falling short of the truth. Barrell thought it probable that isostatic adjustment may be complete only for areas with radii ranging from 100 to 300 if not 500 kilometers, that is, the strength of the outer crust is such "that very considerable stresses can be carried over areas whose radii vary between 100 and 300 kilometers.[18]

The same observations make it seem probable that geodesists have also underestimated the thickness of the loads which the earth's crust is capable of supporting by its strength per given area. Using the mean of all gravity anomalies for the United States as an indication, geodesists assume that the excess load the crust is able to bear is equivalent to the weight of over six hundred feet of rock. Practically the same result is obtained from the mean deflection residuals of the pendulum observations.[19] But geologic evidence favors higher loads and suggests that the crust is strong enough to support rock masses measured by thousands rather than by hundreds of feet. From a further analysis of the geodetic data themselves, Barrell concludes[20] that "the convergence of geodetic evidence shows this crust to be competent to sustain loads measured by the weight of several thousand feet of rock extending over circular areas some tens of thousands of square miles in area. This is a measure of crustal strength twenty-, fifty-, over even a hundredfold greater than that advanced in recent years by the leading champions of high isostasy."[21]

[18] J. Barrell, *op. cit.*, p. 289.

[19] Barrell has corrected an oversight which led to Hayford's statement that the pendulum deflections indicated a much smaller value. *op. cit.*, pp. 299-301.

[20] *op. cit.*, p. 313.

[21] Goranson recently showed that the gravity data from the Hawaiian Islands may be interpreted as consistent with the view that they represent uncompensated loads on the earth's crust. He assumes that the crust is unable to bear such a load and that the islands are actively sinking, that is, moving toward an equilibrium position. But the geological observations adduced as evidence need not be interpreted in his fashion. Goranson points out that if the crust is strong enough to sustain the Hawaiian Islands, it "must be rigid for uncompensated loads in excess of 682 kilograms per square centimeter over areas of 49,100 sq. kilometers." This corresponds to over 8,000 feet of rock of the mean density 2.6 spread over a circular area 222 kilometers in diameter. While extreme, this figure is still of the order of magnitude

Another result of geodetic computations points in the same direction. If the ideal form of the earth is actually that of a triaxial spheroid of the dimensions indicated by the computations of Helmert and Heiskanen, the degree of deviation from the form of an ellipsoid of rotation is in itself evidence that isostatic equilibrium is incomplete. The extra equatorial protuberance inferred from these computations represents an excess load equivalent to 500 or 600 meters (1,600 or nearly 2,000 feet) of surface rock.[22]

That a few hundred feet of rock cannot possibly represent the greatest load the crust is able to bear appears probable also from another line of reasoning. Assume that a load is piled on the surface exceeding the limits of strength of the crust. The load tends to force the crust down after the manner of punching a rivet hole through a metal plate. In order to produce actual deformation, the force exerted by the excess load must overcome the shearing resistance of the crust and the frictional or elastic resistance of the subcrustal materials. Omitting the latter, we can get an idea of the order of magnitude of the stresses involved by assuming the deformation to take the form of a simple shearing fracture around the periphery of a cylindrical block of the earth's crust with the excess load spread uniformly over its surface. By dividing the total excess load by the total area of the vertical shearing surface, we obtain the shearing stress per surface unit.

A simple computation[23] shows that a differential load equivalent to the weight of 500 feet (152 meters) of rock, acting on a cylinder 100 kilometers in diameter and 122 kilometers deep produces a shearing stress equivalent to 8.37 kg. per cm.[23] This result is surprisingly small, only about 1/100 the shearing stress a strong rock can carry at the surface. We have no reason to assume that with increasing depth the shearing strength of the crust decreases to such an extent as to be unable to resist such a small stress. Since our simplifying assumptions were such as to give a maximum result, we can only con-

suggested by other geological phenomena and no or little sinking may be needed to establish isostatic equilibrium. See R. W. Goranson, "The Density of the Island of Hawaii, and Density Distribution in the Earth's Crust," *Am. Jour. Sci.*, 5th ser. Vol. 16, 1928, pp. 89-120.

[22] Review of Heiskanen's *Untersuchungen über Schwerkraft und Isostasie*, by W. D. Lambert, *Am. Jour. Sci.*, 5th ser., Vol. 10, 1925, p. 88.

[23] J. Barrell, *op. cit.*, p. 669.

clude that the crust cannot possibly yield under an excess load of but a few hundred feet of rock.

3. The Nature of Isostatic Equilibrium

While the limits of crustal strength defined in the preceding pages are wider than those favored by most geodesists, they fall far short of the actual relief exhibited by the earth's surface. To bring about isostatic equilibrium whenever a positive or negative load is placed on the crust exceeding the limits of crustal strength, something must happen within or below the crust to offset the excess. And correspondingly, if there is to be a permanent change in elevation at any point of the crust, beyond the limits of crustal strength, something must take place underground in the opposite direction.[24] What it is that occurs is not revealed by the geodetic data.

The elevation of any point on the earth's surface, that is, its distance from the center of the earth, might be controlled solely by the elastic properties of subcrustal matter, after the fashion of boxes of different weight poised at different levels by the springs of a mattress or by the resiliency of a thick rubber sheet. Or the equilibrium might be flotational in which case there should be below the crust a zone of sufficient mobility to make possible a horizontal transfer of matter.

What is known of the physical properties of rock materials makes it seem impossible to interpret the gravitative adjustment of the earth's crust exclusively in terms of elastic strain. A certain amount of horizontal transfer of matter must be involved in the establishment of crustal equilibrium. While all agree with this statement, the widest divergence exists in the minds of both geophysicists and geologists concerning the nature and extent of such horizontal transfer of matter.

T. C. Chamberlin, for instance, denied the existence of anything resembling hydrostatic conditions in the crust. In his last editorial in the *Journal of Geology*, he proposed to substitute the word "elastasy" for "isostasy." "Elastasy would . . . signify a state of balance between the continents and the ocean basins in which elastic strain is

[24] There is "an inevitable tendency for every column of rock in the earth to be of the same weight, and if there is a change . . . at the surface something takes place underground in the opposite direction." R. D. Oldham, in the discussion following Sir S. G. Burrard's paper before the Royal Geographical Society in 1920. *Geog. Jour.*, Vol. 56, 1920, p. 54.

the chief balancing factor, in distinction from hydrostatic equilibrium. When this strain reaches sufficient intensity, idiomolecular readjustment sets in by the transfer of substance, atom by atom, or molecule by molecule, from points of specially intense stress to other points where new attachments may be made, as is so well illustrated in formations undergoing metamorphism. It is a form of reorganization flow—one of the forms of 'solid flow.' It is most familiar in glacial flow as distinguished from lava flow. The concept of elastasy thus leads on to adjustment by motion, but it is not fluidal motion. It is a reorganizing solid flow."[25] Chamberlin assumed this elastic strain to extend to great depths with gradually diminishing intensity.

The other extreme is represented by the views held especially among European geologists. Not only is the equilibrium assumed to be hydrostatic, but it is thought to be maintained by a layer of relatively great mobility present so near the surface that disturbance of the equilibrium sets up subcrustal currents capable of wrinkling the crust into mountain folds. Barrell has set forth the mechanical inconsistencies of this extreme view in a discussion[26] that should be read and answered by all who defend it. Without reproducing his argument the writer wishes here to record his conclusion: "The application of every pertinent engineering principle reduces the initial hypothesis of surface folding by isostatic undertow, and, especially by undertow within the zone of compensation, to an absurdity."

Since the geodetic data can be satisfied by either of these extreme views or any compromise between them, we must look to geologic evidence for a basis for a workable hypothesis concerning the mechanism which underlies crustal equilibrium. From the beginning we found it advisable in this investigation to speak of the earth's "crust." The reason is that the deformations which have affected the outermost part of the earth are those which are exhibited by a thin shell acted upon from within. The evidence for this statement constitutes a major part of this book. Any hypothesis, therefore, which postulates a contrast between an outer "crust" and what lies beneath it fits the geological facts most directly. T. C. Chamberlin's extreme view does not do this.

[25] T. C. Chamberlin, "Intrageology—Elastasy vs. Isostasy," *Jour. Geol.*, Vol. 35, 1927, pp. 89-94 (quotation from pp. 93-4).
[26] J. Barrell, *op. cit.*, pp. 678-80.

On the other hand, geophysical observations seem to show definitely that no continuous layer exists in the outer parts of the earth which has sufficient mobility to deserve being called a liquid in the familiar sense of the word. What lateral transfer there is must take place in a material having the properties of a solid of low strength.

We thus arrive at the picture of an outer layer of the crust endowed with considerable strength and underlaid by another in which the strength is at a minimum, which therefore yields readily under stress. Barrell has shown that such a view is not only consistent with geodetic and geophysical data but is distinctly favored by them.[27]

The same condition was inferred by the geophysicist, Schweydar, from the mathematical analysis of the measurement of the crustal tides by means of the horizontal pendulum. He found that they are in accord with the assumption of the existence of a slightly plastic zone about 600 kilometers thick beneath a more rigid crust 120 kilometers thick.[28]

Barrell calls this zone of weakness the "asthenosphere." It underlies the lithosphere from which it differs by "its inability to resist stress-differences above a certain small limit."[29] To give a clear picture of Barrell's concept of the relation of lithosphere and asthenosphere, his table is here reproduced (Table II) which shows "estimated approximate ratios giving the variation of strength with depth as shown by the nature of departures from isostasy."[30]

TABLE II

Barrell's table of estimated ratios indicating the variation of crustal strength with depth.

	DEPTH IN KM.	CRUSTAL STRENGTH IN PERCENTAGES	
Lithosphere	0	100	Lithosphere
	20	400	
	25	500	
	30	400	
	50	25	
	100	17	
Asthenosphere	200	8	Asthenosphere
	300	5	
	400	4	

[27] J. Barrell, *Jour. Geol.*, Vol. 22, 1914, pp. 729-41; Vol. 23, 1915, pp. 27-44.
[28] Quoted verbatim from J. Barrell, *op. cit.*, Vol. 22, 1914, p. 680.
[29] *op. cit.*, p. 683.
[30] *op. cit.*, Vol. 23, 1915, p. 44, Table 30.

The writer attaches no importance to the numerical values of the percentages shown in this table. They serve merely to illustrate the combined effect of the increase of both temperature and pressure with increasing depth. An increase in temperature with constant pressure or a decrease of pressure at constant temperature would reduce the strength of the asthenosphere still further, and vice versa.

With Schweydar, Barrell assumes the asthenosphere to be several times as thick as the lithosphere. Such a thickness is an important part of Barrell's hypothesis. For in a thick shell of weakness any readjustment "would require but very little viscous shear and but little lateral movement," nothing like the subcrustal "currents" which figure so prominently in other hypotheses. His interpretation of the physical nature of yielding in the asthenosphere is essentially that of T. C. Chamberlin.

While the writer considers Barrell's hypothesis as most consistent with all known facts, geodetic and geophysical as well as geologic, this preference will not prevent us from giving careful attention to the interpretations of structural conditions made on the basis of different hypotheses. We shall judge such interpretations solely by geologic facts leaving aside all arguments derived from speculations concerning the physical nature of the unknown subcrustal regions.

The preceding lengthy discussion has led to two results sufficiently established to enter definitely into our reasoning. We have found a reasonable definition for the concept of the earth's "crust" which we have employed so far only in a vague sense. And we have recognized a factor which limits the vertical extent of crustal deformations. These results we may formulate as follows:

Opinion 3. The "crust" is the outermost shell of the earth, which on the whole possesses sufficient strength to offer resistance to deformation and to transmit long-continued stresses within certain limits.

Opinion 4. As a whole, the crust rests in isostatic equilibrium on the weak asthenosphere. When the vertical stresses set up by local excess loads exceed the limits of crustal strength, vertical movement accompanied by horizontal transfer of matter in the subcrustal asthenosphere restores crustal equilibrium.

4. The Physical Behavior of the Crust

Pratt versus Airy. Having arrived at a concept of the earth's crust which seems consistent with geophysical knowledge, we must turn to the two conflicting ideas concerning its physical behavior which underlie the successful gravity computations of Hayford and Heiskanen.

Hayford postulates that the physical behavior of all parts of the crust is essentially the same. An earth-column undergoing deformation in the center of the Pacific Ocean behaves essentially like a column in the heart of Asia. The heavy and therefore low-lying column behaves like the light and therefore high column. Changes in height are somehow accompanied by changes in the average density; yet in their physical behavior the two columns do not differ materially from each other. This concept was first voiced in 1855 by J. H. Pratt.[31]

Heiskanen's method is based on the ideas of G. B. Airy[32] which were published simultaneously with Pratt's paper. He pictures the crust as made up of two parts of constant average density, but of different strength. The upper part has lower density and higher strength, that is, it is capable of resisting form changes even at depths greater than the average thickness of the crust. The lower part possesses higher density and lower strength, that is, it tends to flow more readily. Columns of different height do not differ in average density, but in thickness. Because of the greater strength of the lighter material, it can be forced down into the asthenosphere and, holding its shape, is buoyed up in it. The higher a column projects above the level of the ocean bottom, the deeper immersed its roots must be to maintain equilibrium. This hypothesis correspondingly has been called the "roots-of-mountains" hypothesis. Like Pratt's hypothesis, it implies a uniform level at which all pressures are equalized. This level lies well down in the plastic substratum, tangent to the deepest "mountain-root."

[31] J. H. Pratt, "On the Attraction of the Himalayan Mountains, and of Elevated Regions beyond upon the Plumb Line in India," *Philos. Trans. Roy. Soc. London*, Vol. 145, 1855, pp. 53-100.

[32] G. B. Airy, "On the Computation of the Effect of the Attraction of Mountain Masses Disturbing the Apparent Astronomical Latitude of Stations in Geodetic Surveys," *ibid.*, pp. 101-4.

It is obvious that from gravity data alone we cannot expect sufficient evidence to decide which of these two alternative views corresponds to reality.

The Airy view inadequate. One argument against Airy's hypothesis has been derived from the gravity anomalies themselves. Bowie has pointed out[33] that the gravitative attraction of an earth column which extends deeply into a heavier substratum by means of a long "root," must be notably less than that of a column of equal weight reaching down to a level of compensation which forms the common base of all columns. The reason for such a difference is that the center of gravity lies considerably lower in the column with a "root" than in the other case. For mathematical purposes, the whole mass of the column may be pictured as concentrated in the center of gravity. Since the gravitative attraction of this mass varies inversely as the square of the distance, gravity over such a column should fall short of its value over columns resting on a common level of compensation. Values of gravity computed with the Hayford equations should, therefore, be too large for all mountain regions. The anomalies should be consistently negative for high regions, the more so the higher the mountains. No such relation between topography and the Hayford gravity anomalies exists (*cf.* Table I, p. 27). This may well be considered an important argument against "roots" of mountains.

A second objection to Airy's hypothesis arises from a consideration of the physical properties required in the rock materials of the lighter portion of the crust. According to the "roots-of-mountains" theory, the rise of a mountain column is the result of a thickening downward as well as upward. Such thickening can be accomplished only through flowage. The matter which forms the roots must be forced plastically into greater depths, into the heavier substratum. Is it, then, imaginable that the same substance should still possess sufficient residual strength to resist flowage under the greater pressures at greater depth? Bowie uses this illustration:[34] "Let us consider the root or roots of the Himalayan Mountains. The average elevation of the Himalayas is not far from three miles. The root must be extensive enough to counterbalance this mountain mass. If the subcrustal

[33] Wm. Bowie, "A Gravimetric Test of the 'Roots-of-Mountains' Theory," *U.S. Coast and Geodetic Survey, Serial 291,* 1924, p. 6.

[34] *idem,* "Notes on the Airy or 'Roots-of-Mountains' Theory," *Science,* Vol. 63, 1926, p. 371-4 (p. 2 of reprint).

material is assumed to be 10 per cent denser than that of the crustal matter forming the root, the downward extension must be about thirty miles. The stress exerted by the plastic subcrustal material on the tip of the root must be equivalent to that exerted under gravity by a column of rock three miles in height. Even though the root may have been formed, and it must have been of very weak material to have been formed, surely it could not be maintained against such enormous stress differences acting since the time the Himalayas were raised." It seems indeed almost inevitable that the "root" would spread out and lose its identity in the plastic basal complex. If no change in density occurred in the column itself, its surface would quickly sink back to the original level.

Recent work on the melting points of acid and basic rocks has demonstrated beyond doubt that "roots-of-mountains" cannot exist. This will be taken up later in this book.[85] It is useful, however, to see that reasoning from independent geodetic and geologic data leads to the same result.

In its extreme form, the "roots-of-mountains" hypothesis assumes the heavier material to lack virtually all strength even near the earth's surface, so that continents and mountains "float" in it as icebergs are buoyed up in water. Many of the details of the earth's surface testify against this extreme view.

Its adherents speak, for instance, of the oceanic level as if it were a uniform surface controlled by the laws of hydrostatics. If the heavy substratum differs so much from the lighter portion in lack of strength, such a uniformity seems almost inevitable. Yet the actual conditions are far from agreement with such a postulated uniformity. The vast floor of the Pacific is spoken of especially as the visible surface of the yielding substratum of the continental blocks. Yet the northern half of the Pacific is much deeper than the southern part. More than half of its area lies at a depth exceeding 16,400 feet (5,000 meters) while the average depth of the southern Pacific is only 12,900 feet.[86] A difference in average elevation of 3,500 feet between large

[85] See pages 301-2.

[86] Erwin Kossinna, "Die Tiefen des Weltmeeres," *Veröff. Instit. f. Meereskunde d. Univ. Berlin*, N.F., Reihe A, H. 9, 1921, p. 33. (The average depth of the northern Pacific is given as —4,753 meters, that is, nearly 15,600 feet.)

divisions of the surface of the substratum certainly does not speak for a high degree of yielding.

The concept of great differences in the strength of the rock materials of the ocean floors and continental platforms is contrary to the contents of law 6: " 'Welts' and 'furrows' similar in form and dimensions exist at the level of the ocean bottoms as well as on the continental platforms." Since this law appears definitely established we are compelled to admit that, in physical behavior, there is no great difference between the crust in oceanic areas and on continents. This is directly implied in our opinion 1 (p. 14). If this opinion is correct, there cannot be any "continental drift."

We are thus led to ascribe physical reality to the mathematical concept which underlies Hayford's computations. The resulting concept of the crust is fundamental for all that follows. It is purely physical and is independent of any chemical variations in the rock materials of the crust. It merely states that wherever one may descend radially downward from the earth's surface, one will ultimately reach the base of the crust at a depth beneath sea level which is not far from constant for the whole earth.

Opinion 5 a. The base of the crust is a markedly uniform level at which the residual strength of the crust approaches zero. This is the upper limit of the "asthenosphere."

Opinion 5 b. Aside from the influence of localized stresses, the strength of the earth's crust is of the same order of magnitude in all its parts at comparable levels, that is, no part shows a significantly higher plasticity than any other.

5. Elevation versus Density of Igneous Rocks

In order to satisfy the demands of the law of compensation, changes in the elevation of crustal columns must somehow be accompanied by changes in density. Having found the simpler assumption of Airy inadequate, we must face the question of the nature of these changes in density. Are they connected with changes in the material of the crust or are they chiefly the expression of changes in the texture of the rock materials, the states of matter involved and other physical transformations at present still more or less obscure?

Two general observations, here designated as Washington's and Wegener's laws, suggest independently that changes in the proportions of heavy and light materials play an important, perhaps the dominant, part in the change of average density within units of the earth's crust.

Washington's Law. The first of these is concerned with the average density of the igneous rocks found over large units of the earth's surface. H. S. Washington has investigated the relation which exists between the average density of the igneous rocks and the elevation of various regions. He has summarized his results in the following law:[87]

Law 10. For large units of the earth's surface, the average density of the exposed igneous rocks varies roughly with the inverse of the average altitude.

Washington calculated the average densities from the published chemical analyses of igneous rocks. For the methods of computation and detailed results the reader is referred to the original publication. We reproduce here the two charts[88] (Figs. 8 and 9) in which the densities are plotted against the elevations of the areas. For each area, the average density was computed twice, for a water-free condition of the rocks and for water-bearing rocks. The two densities are represented in the charts by dots and crosses respectively. The numbers refer to the areas listed in the legend of the charts.

A study of the charts shows that the relation is far from simple. In his paper, Washington has discussed the factors of uncertainty which enter into the computations and obscure the general relation. Yet, at least for areas of continental and oceanic extent, the figures seem to prove that "the higher parts of the crust are composed of or underlaid by relatively light material, while the lower parts are underlaid by heavier material. This . . . is precisely the relation demanded by the theory of isostasy."[89] Assuming that for large areas the average density of the igneous rocks present at the surface is virtually equal to the average density of the corresponding crustal column, Washington computed the lengths the various blocks must

[87] H. S. Washington, "Isostasy and Rock Density," *Bull. Geol. Soc. America*, Vol. 33, 1922, p. 393. See also H. S. Washington, "The Chemistry of the Earth's Crust," *Jour. Franklin Inst.*, Vol. 190, 1920, pp. 757-815, esp. pp. 799-815.

[88] Reproduced from H. S. Washington, *op. cit.*, Figs. 1 and 2, pp. 394 and 396.

[89] H. S. Washington, *op. cit.*, p. 398.

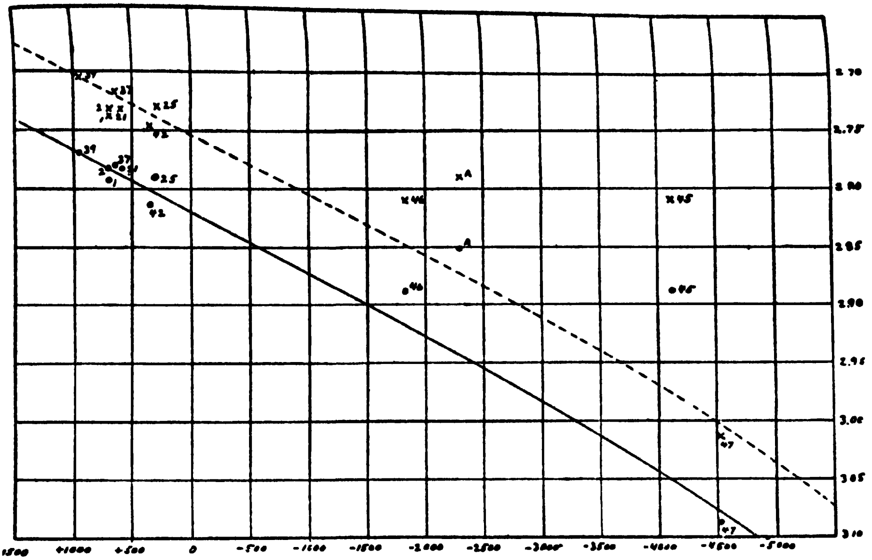


Fig. 8. Average densities of continental and oceanic areas plotted against average altitudes.

NOTE: The dots represent densities computed for water-free rocks, the crosses densities computed for water-bearing rocks. The numbers refer to the following areas (figures in parentheses give the number of analyses used in calculating the average density):

1: Earth (5,159)
2: North America (1,709)
21: South America (138)
25: Europe (1,985)
37: Africa (223)
39: Asia (114)
42: Australia (287)
45: Atlantic (average depth) (56)
46: Atlantic ridge (56)
47: Pacific (72)

have to be of equal weight. When in equilibrium the level of the bases of the various blocks must be that of a spheroidal surface lying at a virtually constant distance below sea level, the "depth of compensation" of Hayford and Bowie.[40]

From the given average elevations of the crustal columns and the computed average densities Washington calculated the depth of compensation,[41] using different combinations of columns. The best value he obtained is 59 kilometers. This figure lies well within the limits for the depth of compensation obtained by Bowie from gravity deter-

[40] Washington introduces the term "isopiestic level" which has the advantage of being free from suggestions concerning "compensation" which may bias reasoning.

[41] *op. cit.*, p. 403.

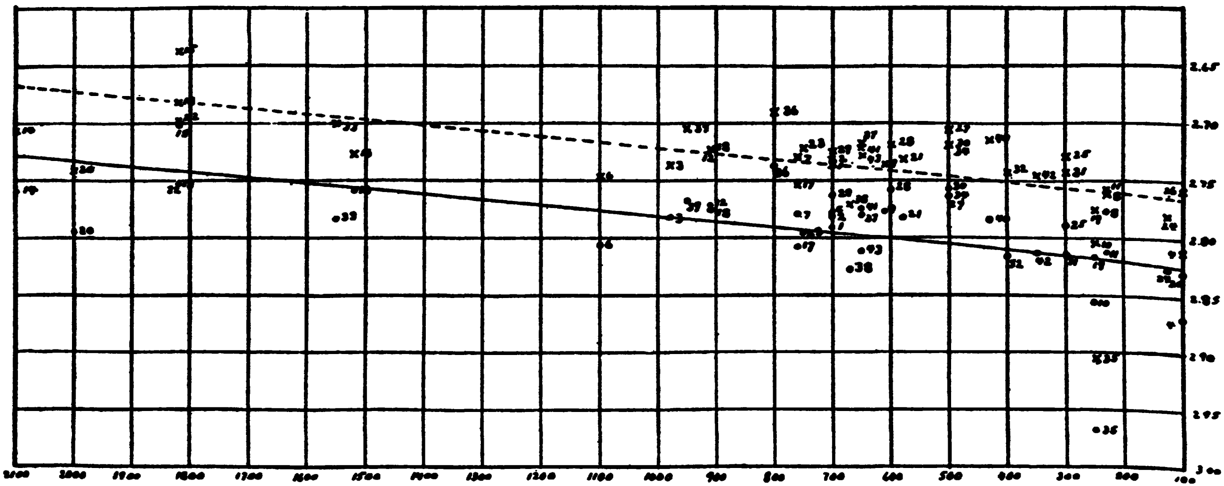


Fig. 9. Average densities of land areas plotted against average altitudes. (For explanation see legend of Fig. 8)

3: Greenland (41)
4: Ontario (99)
5: Alaska (24)
6: British Columbia (60)
7: United States (1,351)
8: New England and New York (213)
9: Appalachian (188)
10: Algonkian region (66)
11: Arkansas-Texas (50)
12: Montana (133)
13: Wyoming (Yellowstone National Park) (134)
14: Colorado (171)
15: Utah-Nevada (79)
16: Arizona-New Mexico (79)
17: Oregon-Washington (51)
18: California (175)
19: West Indies (82)
20: Mexico and Central America (47)
22: Andes (56)
23: Eastern Brazil (20)
24: British Guiana (45)
26: Great Britain and Ireland (171)
27: France (163)
28: Scandinavia (313)
29: Norway (107)
30: Sweden (206)
31: Germany (474)
32: Austria Hungary (without Tyrol) (148)
33: Switzerland and Tyrol (219)
34: Italy (276)
35: Russia (chiefly Urals) (98)
36: Greece and Archipelago (33)
38: Madagascar (140)
40: Japan (69)
41: Malaysia and Philippines (129)
43: New Zealand (134)
44: Antarctica (103)

minations. It is almost identical with the figure obtained from the use of 216 gravity stations distributed over the United States. This figure is 60 kilometers. Such agreement between the results obtained by two entirely independent methods makes it probable that the depth of about 60 kilometers actually marks about the level above which crustal columns are approximately of equal weight. Correspondingly, the average density of the igneous rocks visible at the surface appears to bear actually a definite relation to the average density of the block as a whole. Applied to the largest units of the earth's surface this means that rocks of widely different character make up the large oceanic and continental units.

This conclusion is confirmed by seismological observations. The analysis of the times of arrival of preliminary tremors recorded at stations located short distances from the epicentra of earthquakes shows that the velocity of earthquake waves is different beneath the continents and the oceans. Although the number of reliable data is still small, the following general conclusions seem justified.[42] Beneath the continents[43] earthquake waves seem to travel with low velocities down to a depth of 50 to 60 kilometers. Beneath the Pacific Ocean, on the other hand, they travel with high velocities, practically from the surface downward. In the Atlantic and Arctic Oceans, lower velocities seem to be limited to an upper layer about 20 to 30 kilometers thick, below which the velocities are like those found beneath the Pacific Ocean.

But the velocities of earthquake waves depend on the physical properties of the materials through which they travel, especially on their compressibility and rigidity. The differences in the velocities of earthquake waves are such as would result from the differences in the physical properties of acid and basic igneous rocks. The earthquake records make it probable, therefore, that the crust beneath the continents consists largely of light, acid rock materials. Beneath the Atlantic and Arctic Oceans, the relatively acid outer layer seems to be only some 20 to 30 kilometers thick, while it seems to be practically absent below the floor of the Pacific Ocean.

[42] B. Gutenberg, *Der Aufbau der Erde*, Berlin, 1925, pp. 95-119.
[43] Adequate data are available only for Eurasia and America.

Using Washington's figures of the average surface densities as starting points, assuming a depth of compensation of 60 kilometers and the distribution of light and heavy materials indicated by seismology, Gutenberg computed the average rock densities in the outermost layers of the earth as follows:[44]

TABLE III

Probable average densities of the rock materials in the uppermost levels of the earth.

(After B. Gutenberg)[45]

DEPTH IN KMS.	EURASIA, AMERICA	ATLANTIC OCEAN	PACIFIC OCEAN
0	2.75	2.85	3.05
10	2.8	2.9	3.1
20	2.8	2.9	3.1
30	2.9	3.1	3.1
40	2.9	3.1	3.1
50	2.9	3.2	3.2
60	3.2	3.2	3.2
70	3.2	3.2	3.2
80	3.2	3.2	3.2

The figures in this table should be compared with the typical densities of the chief igneous rock types as computed by Adams and Williamson:[46]

TABLE IV

Table of densities of important plutonic rock types under pressures corresponding to a depth below the surface of—

	6 KM.	33 KM.
Granite	2.61	2.66
Granodiorite	2.69	2.73
Syenite	2.61	2.66
Diorite	2.74	2.78
Gabbro	3.05	3.08
Pyroxenite	3.40	3.44
Peridotite	3.40	3.44
Dunite	3.38	3.41

[44] The increase of density with depth was assumed to depend practically on pressure only, for which case the equation published by Williamson and Adams in 1923 was available. (E. D. Williamson and L. H. Adams, "Density Distribution in the Earth," *Jour. Washington Acad. Sci.*, Vol. 13, 1923, p. 413.)

[45] B. Gutenberg, *Der Aufbau der Erde*, Berlin, 1925, p. 117, Table 56.

[46] L. H. Adams and E. D. Williamson, "The Compressibility of Minerals and Rocks at High Pressures," *Jour. Franklin Inst.*, Vol. 195, 1925, p. 520.

While the figures in Table III cannot be considered quantitatively accurate, they indicate probably correctly the order of magnitude of the changes involved. It should be remembered that they are hypothetical. They are introduced to show concretely the distribution of densities which must prevail if the opinion derived from Washington's law seen in the light of seismological analysis is correct:

Opinion 6. Beneath the continents the earth's crust consists dominantly of light, acid materials, down to a depth of 50 to 60 kilometers; beneath the Atlantic and Arctic Oceans light acid materials are limited to an outer layer 20 to 30 kilometers thick; while beneath the Pacific Ocean the crust seems to consist almost wholly of heavy, basic rock materials.

This opinion is so well founded that it might have been listed among the laws. If we were concerned solely with the chemical-petrographic character of the materials, we could speak of the acid "crust" which is absent beneath the Pacific Ocean. The seismologist is likewise inclined to use the word "crust" in this petrographic sense, because of the different behavior of acid and basic materials toward the short-time impulses of earthquake waves.

But in the study of the permanent deformation of the earth's crust, neither the petrographic characters (e.g. density) nor the resistance to deformation by short-time impulses ("rigidity") enter as essential factors. The only property which counts is the resistance of the rock materials to permanent deformation ("flow") by the prolonged action of forces which is called "strength." There is no connection between strength and the other two properties mentioned. Differences in the one do not measure or even indicate differences in the other. The only way to find out if there is a significant difference in the behavior of the basic and the acid materials of the crust under the action of earth forces applied during long intervals of time is to compare the results of deformations on ocean floors and on continental platforms. This we have done. Law 6 (also law 43) shows that no significant differences exist.

The preceding discussion leads to the conviction that differences in the rock materials are primarily responsible for the differences in the average densities of the various units of the earth's crust. Returning to Washington's law, we observe that it does not hold good merely for units of continental dimensions, but for smaller regions

within the continents. What can such a relation mean? Why should the average density of the igneous rocks now exposed at different parts of the continental surfaces bear a relation to the altitude of these parts? Certainly such a relation cannot be the expression of a primary, permanent condition. That would be contrary to the fundamental law of the reversibility of the radial crustal movements (law 2, page 2). Indeed, the most elementary knowledge of the geological history of any region tells us that at different times of geological history a similar study of the outcropping igneous rocks would have yielded very different results.

Take, for instance, the low plateaus north and south of the Ohio River from Ohio and Kentucky to Illinois. On the northeast shore of Georgian Bay the ancient surface of the Canadian shield dips beneath the Paleozoic sediments of the tablelands to the south. In the Blue Ridge of Virginia it emerges again. In both regions granitic rocks dominate greatly among the outcrops of igneous rocks. Almost exactly halfway between Georgian Bay and the Blue Ridge the drill reached the old pre-Cambrian land surface twice[47] at a depth of about two thousand seven hundred feet beneath the surface, approximately two thousand feet below sea level. The drill found granite (perhaps granite-gneiss). The rocks that outcropped on this old land surface, then, were dominantly granitic. This is true whether that surface today lies a thousand feet above sea level or two thousand feet below, at least over a range greater than that covered by the figures plotted in Fig. 9.

At first sight this seems contrary to Washington's law. That law, however, applies to the present position of the crust. When we look for the products of volcanic activity since the downwarping of the old surface beneath the Paleozoic rocks of the plateaus, we find them to be basic rocks, largely peridotites. Such is the material of the dikes and plugs of Pope, Hardin, and Sabine Counties, Illinois; the dikes of Crittenden and Caldwell Counties of western Kentucky; the isolated dike in Elliott County in eastern Kentucky; the Masontown

[47] In 1912, in the Norris well, three miles northeast of Findlay, Ohio, at a depth of 2,770 feet, starting about 830 feet above sea level; in 1927, in the Bruns well, three miles south of Woodville, Ohio, at a depth of 2,675 feet, starting 655 feet above sea level.

dike of southwestern Pennsylvania; and the dikes of western New York.

The familiar trap sheets and sills of the Triassic lowlands east of the Green Mountain-Blue Ridge axis of the Appalachian system illustrate the same peculiar relation. Granitic rocks dominate on the peneplains of New England and the Piedmont provinces. We have no reason to doubt that these same rocks form the floor of the Triassic basins. Yet, when that floor began to sink, basic rocks rose to the surface.

In the Californian Coast Ranges, basic rocks, from basalts to peridotites (now largely serpentinized), rose toward and out upon the surface of the sinking belt in which the Franciscan sediments were accumulating. During the later orogenic movements, on the other hand, quantities of acid rocks including much rhyolite poured out on the surface.

These illustrations deal, of course, with rather extreme and simple cases. They were chosen because they seem to show that the character of the rising bodies of magma changes when the direction of crustal movement changes.

It looks as if basic materials were brought up into the superficial portions of a sinking continental unit, while the acid intrusives in rising mountain chains suggest a concentration upward of the more acid materials of the crust during orogenic movements. If there were reason to extend this general picture to the crust as a whole, it would mean that sinking is accompanied by the introduction into the crust of heavy rock materials from beneath, while rising is accompanied by downward expulsion of basic materials. We shall see later that there are independent reasons for such an assumption. But for the present we are merely concerned with the outlook gained which indicates that the distribution of rock types within the crust need not be constant, but may change materially in consequence of the deformation which creates the differences of surface elevation.

6. The Two Dominant Levels of the Earth's Surface

Wegener's law. The great thickness of lighter materials under the continental portions of the crust may be inherited from the days of a liquid outer earth. Again, they may be the final result of often

repeated selective processes connected with the upward movements. Or again, both possibilities may be involved, an original condition having been intensified by the mechanism involved in upward movements. It seems plausible that an original condition plays a rôle in the distribution of densities.[48] The conviction is widely held, however, that the difference is wholly primary. It is based on the observation that two levels dominate on the earth's surface. This generalization is of sufficient importance to be formulated here as a law, although our concept of "law" has to be stretched perhaps unduly to include it.

Law 11. The frequency curve of elevations on the earth shows two pronounced maxima, corresponding to the ocean floors and to the continental platforms.

The heavy line in Fig. 10[49] represents graphically the contents of this law. Expressed in percentages, the frequency of the various levels is given by H. Wagner[50] as follows:

	DEPTH BELOW SEA							ELEVATION ABOVE SEA			
Below	6	5–6	4–5	3–4	2–3	1–2	0–1	0–1	1–2	2–3	Above 3 km.
	1.0	16.5	23.3	13.9	4.7	2.9	8.5	21.3	4.7	2.0	1.2 per cent

"In the whole of geophysics there is scarcely another law of such clearness and certainty as this one, which states that there are two favored levels on the earth, which occur alternately side by side and which are represented by the continents and the floors of the oceans." We are quoting from the beginning of Wegener's exposition of the facts which lead to his theory of floating continents.[51] He continues: "If . . . only a single equilibrium level existed, disturbances thereof, such as elevations and subsidences, could then only give rise to two differing frequency-maxima, if physical causes existed for a preference of just these elevations. Since this is not the case, the frequency should simply be controlled by the law of errors of Gauss, because the

[48] See, e.g., p. 457.

[49] Alfred Wegener, *The Origin of Continents and Oceans* (translated from the third German edition by J. G. A. Skerl), New York (Dutton), 1924, Fig. 5, p. 30.

[50] Hermann Wagner, *Lehrbuch der Geographie*, Vol. I, *Allgemeine Erdkunde*, Part 2, *Physikalische Geographie*, Hannover (Hahn), 1922, p. 271. These figures include the results of Kossinna's recent statistical analysis of Max Groll's bathymetric maps of the oceans. Erwin Kossinna, "Die Tiefen des Weltmeeres," *Veröff. Instit. f. Meereskunde d. Univ. Berlin*, N.F., Reihe A, H. 9, 1921.

[51] *op. cit.*, pp. 30–1.

deviations from the level of equilibrium must naturally be fewer as they become greater. Thus there should exist a single frequency-maximum somewhere in the region of the mean sphere level (—2,450 meters). Instead of this we see two maxima, both of which have a curve with a course similar to that of the law of errors. From this it must be concluded that there are already two undisturbed original levels, and from this the step seems inevitable, that in the continents and the floors of the oceans we have two different layers of the body of the earth, which—expressed in a somewhat exaggerated form—act as water does between great sheets of ice. This step seems so easy and obvious that the next generation will certainly wonder that we should have hesitated such a long time over taking it." The logic of this argument hinges on these two sentences: "If . . . only a single equilibrium level existed, disturbances thereof . . . could then only give rise to two differing frequency-maxima, if physical causes existed for a preference of just these elevations.[52] *Since this is not the case. . . .*" Is there really no other physical cause for the "preference" of the level of continental platforms than flotational equilibrium of the lighter crustal scum? The Canadian shield furnishes a respectable part of the values for the North American continental platform. Every foot of it bears evidence that it suffered forceful displacement upward, and that the original elevation from point to point must have varied widely between syn-

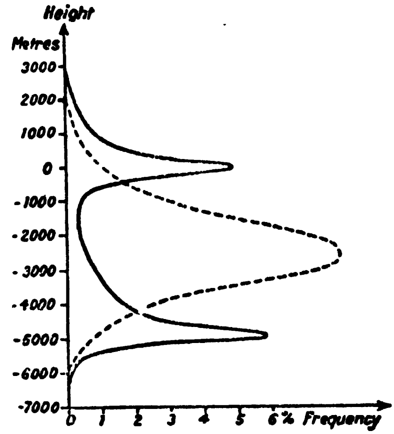


Fig. 10. Graph showing the two frequency maxima of elevation on the earth's surface.

Solid line = actual frequency of elevations based on a contour interval of 100 meters. Dotted line = hypothetical frequency of elevations representing the result of disturbances of a single equilibrium level, with deformation accomplished as easily downward as upward.

(A. Wegener, 1922; reproduced from *The Origin of Continents and Oceans*, by permission of E. P. Dutton & Co.)

[52] For objections to this statement on mathematical grounds, see G. V. Douglas and A. V. Douglas, "Note on the Interpretation of the Wegener Frequency Curve," *Geol. Mag.*, Vol. 60, 1923, pp. 108-11.

clinal regions and the centers of large anticlinal belts of plutonic intrusions. No man knows what the surface of the Canadian shield would look like had there been no erosion. But everybody knows that it would not be level and very far from its present elevation. Both, the level surface and the present elevation, are the product of erosion, chiefly by running water, tied to a lower limit by the surface of the ocean, the "base-level of erosion," which it approaches asymptotically. This is the veriest commonplace of geological knowledge.

What is true of the Canadian shield is true of the lowlands of the whole continent, and of all continents, that the structure of the Archean basement at least and in very large regions of younger rocks shows the results of forcible uplift to most diverse heights, later reduced to a uniform level by degradation.

The same external forces of erosion have filled up the downward deflections to the same limiting level. The great furrows filled with Tertiary sediments all contribute to that second maximum in the frequency curve of elevations. The large negative gravity anomalies all along the coastal plain tell us of great thicknesses of Cenozoic sediments extending from the former inland shores to the continental shelf.

With the assumption that the mean continental surface is a primary level of equilibrium, Wegener couples a second, equally objectionable argument. He contrasts the observed curve of frequencies with one that should prevail if there were only one level of equilibrium subject to deformation according to Gauss' law. The appeal to Gauss' law of errors is justified only if the errors are free to fall equally on both sides of the maximum. This must be proved before an appeal to this law is justified. Such a proof in our case would involve the whole mechanism of earth deformation, the very problem to be solved by appeal to this law! A concrete illustration may serve to show that we have reason to doubt the applicability of Gauss' law of errors.

Within a mile or two of each of the mouths of the Mississippi, lie large upheavals of clay[58] which have become known as "mud lumps." They are commonly 300 to 500 feet broad and stand 20 to

[58] E. W. Shaw, "The Mud Lumps at the Mouths of the Mississippi," *U.S. Geol. Survey, Prof. Paper 85*, 1913, pp. 11-27.

30 feet above the adjacent bottom. "With reference to sea level their heights are somewhat closely concordant, few extending more than 8 or less than 2 feet above the water." No doubt a frequency curve of elevations of a mud lump region would closely resemble that of terrestrial elevations. Here, moreover, the flat surface that tops the elevations is not due to erosion but probably represents a surface of equilibrium between opposing forces. The visual as well as the supposed statistical evidence, as interpreted by Wegener, would certainly confirm comparison with floating cakes of ice. Yet even Wegener would admit that such a conception of the nature of the mud lumps would be preposterous. The evidence points to a structure such as is shown in the section reproduced in Fig. 11.[54] Here, then, we have a

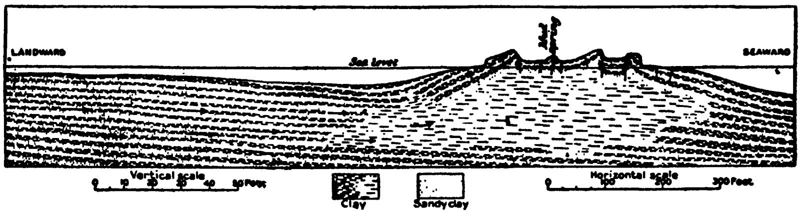


Fig. 11. Partly hypothetical cross-section of one of the mud lump islands at the mouth of the northernmost arm of the Mississippi delta. The arrows show the supposed flowage of the clay layers from the landward side.

(E. W. Shaw, 1913)

case of two dominant levels in which both levels are controlled by the mechanics of the layer which they bound. And yet it would be impossible to apply to it Wegener's line of reasoning.

We have introduced the mud lumps here for a more specific purpose. Suppose the mud lumps were not forced up under a common regional control but under localized conditions of equilibrium. Then they would not rise to uniform levels and there would be but one dominant level, viz., the floor they stand on. This would correspond to the "single equilibrium level" undergoing disturbances of Wegener's passage quoted above. But there would be no possibility of deforming this level downward or it would be much more difficult at least than to deflect it upward. If we should plot the resulting curve of elevations, it would be of the nature of Fig. 12, but not

[54] *op. cit.*, Fig. 6, p. 24.

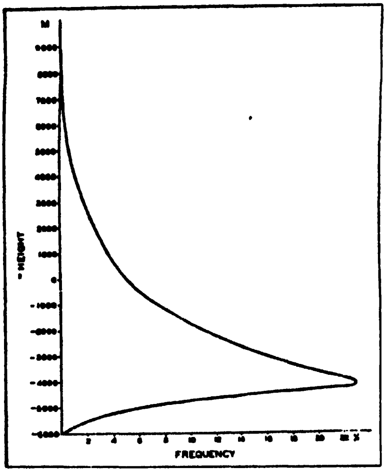


Fig. 12. Hypothetical graph showing the frequency of elevations on the earth's surface resulting from the disturbance of a single equilibrium surface, with deformation much easier to accomplish upward than downward. (Frequency based on 1,000-meter contours.)

like the dotted line in Wegener's graph (Fig. 10). It seems significant that the familiar hypsographic curve of the earth's surface (Fig. 13) assumes a form similar to this when we attempt to smooth out the effects of erosion and deposition. This is shown in Fig. 13*a*. The dotted line cuts from the hypsographic curve an area which is comparable in size to the empty space between the curve and the dotted line above. It is not unreasonable to suspect that the first area represents the rock materials eroded from the space now occupied by the second. Such an interpretation is at least as reasonable as the implicit assumption in Wegener's argument.

From this interpretation of the hypsographic curve inferences may be drawn which are in harmony with our general ideas concerning the condition of the earth's crust. (1) Upward deformation greatly preponderates over the downward part of the curve. This would mean that it is easier to raise the earth's crust than to depress it. (2) As the height of the curve increases, its width decreases rapidly. This would indicate that the difficulty required to raise a part of the earth's surface increases with the height. The elevations seem to approach an upper limit. Washington's law may mean that this limit is connected with the range of densities of crustal materials. It is not profitable to follow these speculations farther.

The preceding comments suffice to justify the following opinion:

Opinion 7. The two frequency maxima of elevations on the earth owe their existence to the action of two independent sets of forces. The dominant lower one, that of the ocean floor, owes its existence to

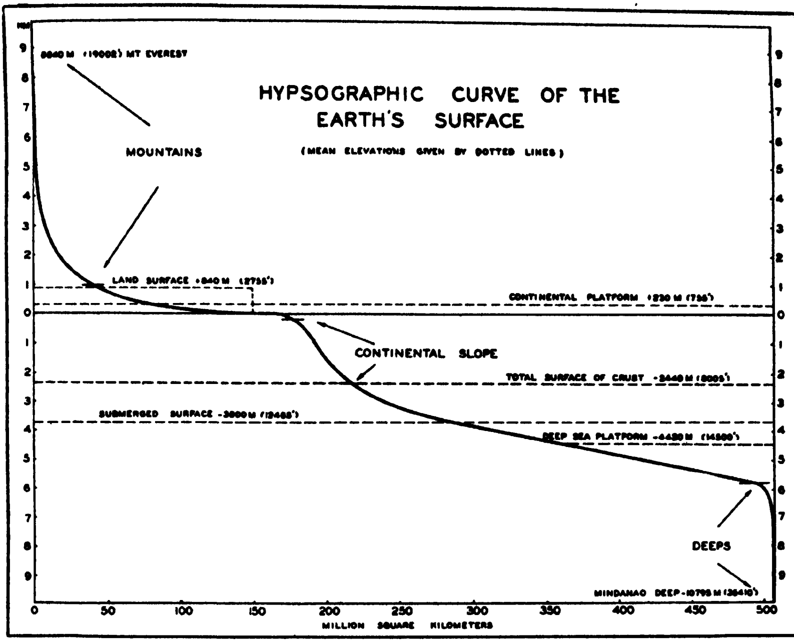


Fig. 13. Hypsographic curve of the earth's surface. The following *mean elevations* indicated by dotted lines:

Mountains:	+2,040 m. = 6,695 ft.	
Land surface:	+840 m. = 2,755 ft.	
Continental platform:	*+230 m. = 755 ft.*	
(from —200 m. to + 1,000 m.)		
Total surface of crust:	—2,440 m. = —8,005 ft.	(—1,334 fathoms)
Submerged surface of crust:	—3,800 m. = —12,465 ft.	(—2,077 fathoms)
Deep-sea platform:	—4,420 m. = —14,500 ft.	(—2,417 fathoms)
Deeps:	—6,100 m. = —20,000 ft.	(—3,333 fathoms)

(*Redrawn, with minor changes and omissions, from E. Kossinna,* 1921)

the dynamics of the lithosphere. The upper is the work of the atmosphere acting through erosion and sedimentation toward the limiting level, the surface of the sea.

Wegener's law was introduced here for a special purpose. The essence of the opinion just formulated is that the higher portions of the earth's crust mark those regions where sections of the crust were compressed, that is, were shortened horizontally and lengthened vertically. Since by definition the base of the crustal column corre-

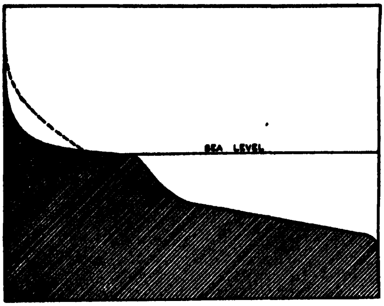


Fig. 13a. The actual hypsographic curve of the earth's surface (solid line) compared with the condition represented in Fig. 12 (dotted line).

sponds, however, to the depth below which the pressure exceeds the strength of the materials, the basal portion of a column which is made taller by compression must lose its strength and spread out below the crust, ceasing to be part of the crust. Since the basal portion consists of the heaviest materials, this process automatically reduces the average density of the compressed column, so far as it enters into the isostatic equilibrium. Thus Wegener's law, in the last analysis, leads to a second method by which the average density of sections of the earth's crust may suffer changes in connection with those processes which cause changes in the surface elevations. We shall return to this line of reasoning later, and shall see then that it may be applied successfully to sinking regions as well.

7. External Versus Internal Factors of Crustal Disturbance

Having formed definite opinions concerning the composition of the crust and the nature of crustal equilibrium, we can now turn to the question which concerns us more directly. What are the chief factors that enter into a disturbance of crustal equilibrium?

Since Dutton's famous address before the Philosophical Society of Washington in 1889, erosion and sedimentation are considered especially by American geologists as the chief motive power behind changes of level on the earth's surface. Dutton expressed this view as follows:

"Where great bodies of strata are deposited they progressively settle down or sink seemingly by reason of their gross mechanical weight, just as a railway embankment across a bog sinks into it." As to mountains "the flanks of . . . [mountain] platforms with the upturned edges of the strata reposing against them or with gigantic faults measuring their immense uplifts, plainly declare to us that they

have been slowly pushed upward as fast as they were degraded by secular erosion."[55]

T. C. Chamberlin lent the weight of his great mind to this hypothesis. Recently Bowie expressed it in these words: ". . . The primary causes of at least the major changes of the earth's surface are evaporation, precipitation, erosion and sedimentation."[56]

The concept of isostatic equilibrium implies that deposition and erosion enter into crustal deformation as factors insofar as their effects exceed the limits of crustal strength. The question is, do they enter as decisive factors? If they do we must find them both necessary and sufficient to account for the regional distribution and the magnitude of vertical movements in the earth's crust.

The details of the regional distribution of welts and furrows will occupy us later. Here we confine ourselves only to one aspect which is expressed in the following law:

Law 12. "Furrows" exist similar in shape and dimensions, both filled with sediments (geosynclines of the past and present) and as hollow surface forms (furrows in oceanic deeps). Similarly, "welts" exist in the form of mountain ranges both beneath the cover of the ocean (where they never suffered degradation) and above it (exposed to erosion).

The examples given in the discussion of law 5 may serve to illustrate this law. Any good bathymetric chart of the Pacific or Indian Oceans will furnish pertinent material. The obvious facts comprised in this law inevitably lead to the conclusion that erosion and deposition are not necessary to the formation of welts and furrows. Are they sufficient?

Take the case of marine sediments accumulating on a sea floor 100 feet deep. Let this sea bottom be built up with sediments to the surface. Assume the density of the sediment to be four-fifths of that of the subcrustal region. Then the mass of the 100 feet of sediment equals that of only 80 feet of subcrustal matter which is forced out below. The sea floor, originally 100 feet below the water surface, will

[55] C. E. Dutton, "On Some of the Greater Problems of Physical Geology," *Bull. Philos. Soc. Washington*, Vol. 11, 1889, pp. 51-64. Quoted from reprint in *Jour. Washington Acad. Sci.*, Vol. 15, 1925, p. 361-2.

[56] Wm. Bowie, *Isostasy*, New York, 1927, p. 267. See also: "Proposed Theory, in Harmony with Isostasy, to Account for Major Changes in the Elevation of the Earth's Surface," *Beitr. z. Geophysik*, Vol. 15, Heft 2, 1926.

be depressed only an additional 80 feet. Successive amounts of depression of the floor will be 100 feet, 80 feet, 64 feet, 51 feet, 40 feet, etc. If we call the original depth a, the series can be written— a, $\frac{4}{5}a$, $\frac{4}{5}^2a$, $\frac{4}{5}^3a$, . . $\frac{4}{5}^na$. This infinite geometric series converges to the sum $\frac{a}{1 - \frac{4}{5}} = 5a$. For an original depth of 100 feet, this mechanism, under the assumptions made here, gives 500 feet as the maximum depression of the sea bottom. If the ratio of crustal to subcrustal densities should be as low as 9:10, the maximum possible accumulation of sediments provided by this mechanism is 1,000 feet.

Compare with this some of the great thicknesses of sediments observed. In the Appalachian geosyncline as much as 38,000 feet of sediments[57] were deposited during the Paleozoic alone, and in the Rocky Mountain geosyncline Mansfield[58] recently reported something like 45,000 feet of sediments laid down in Paleozoic and Mesozoic times, without conspicuous deformation at any time during that long interval. In both regions, the larger part of the sediments was deposited in shallow water and on alluvial plains, that is, in places incapable of being built up higher at any time than a very few hundred feet above the starting point. The same is true for the thousands of feet of shallow water sediments that cover the "swells" and "basins" of the interior lowlands.

Certainly then the mechanism provided by sedimentation and erosion for the sinking and rising of earth columns is not sufficient to account for the plain facts of geologic observation. This is generally recognized by geodesists. Bowie,[59] for instance, says: "If the only activity in the column were one to perfect the isostatic balance as sedimentation proceeded, then there would be a gradual rising of the surface of the sedimentary area as the light material was deposited, until sedimentation ceased. In order that the condition of isostasy may exist there must be increases and decreases of density in the isostatic shell. . . . We must conclude that the material in the column

[57] Charles Schuchert, "Sites and Nature of the North American Geosynclines," *Bull. Geol. Soc. America*, Vol. 34, 1923, p. 175.

[58] G. R. Mansfield, "Geography, Geology, and Mineral Resources of Part of Southeastern Idaho," *U.S. Geol. Survey, Prof. Paper 152*, pp. 48-52.

[59] Wm. Bowie, "Isostatic Investigations and Data for Gravity Stations in the United States Established Since 1915," *U.S. Coast and Geodetic Survey, Spec. Pub. 99* (Serial No. 246), 1924, p. 46.

under the sediments has increased in density. The cause of this increase in density is, of course, not known, but it may have been due to some chemical or physical action other than the ordinary thermal contraction. Whether all of the shrinking of the column and increase in the density of material occurred during the sedimentary period or whether some of the change took place before sedimentation started is also unknown, but probably some of the change took place before sedimentation started and decided the area in which sedimentation occurred."

The outcome of this discussion is, then, the exact opposite of the view still held by many:

Opinion 8. Erosion and sedimentation are neither necessary nor sufficient to account for the sinking of "furrows" or the rising of "welts."

We must, therefore, look below the surface for the factors that control the shifting fates of the face of the earth. In doing so, we must not forget, however, that the isostatic behavior is a reality, causing all changes in the distribution of rock materials to be followed by changes in elevation so far as they tax the crust beyond its strength. But isostasy does not create, it only modifies.[60] During much of the following discussion, we may safely neglect it.

[60] "Isostasy, though a working principle, can be overworked. . . . It is not a force. . . . It is merely a tendency to get things into a state of balance or, if in equilibrium, to keep them so." R. T. Chamberlin, "Isostasy from the Geological Point of View," *Jour. Geol.*, Vol. 39, 1931, pp. 1-23.

CHAPTER III

CONTINENTAL MARGINS AND INTRA-CONTINENTAL MOBILE BELTS

"Keine Sache wird klarer, wenn man Hypothesen auf Hypothesen häuft."
A. Supan, in *Grundzüge der physischen Erdkunde.*

1. Continental Margins

Superstructure and Substructure of Continents. In the preceding chapter we arrived at the opinion that the fairly uniform elevation of large expanses of continental lowlands is not simply the expression of a gravitative equilibrium between the continental masses and the heavier substratum of the oceanic segments. Wherever we investigate the structure of the visible outermost portion of the earth's crust, we find evidence of profound transformation through folding, magmatic intrusion, and metamorphism at elevations which indicate also uplift. In the centers of the recent mountain belts this evidence lies at the surface. In the large tablelands the strongly deformed rock forms a substructure which lies more or less concealed beneath a superstructure[1] of essentially undeformed later sediments. The unconformity which separates these two structural units ranges, of course, through all divisions of geological time. In many places, also, more than one such major unconformity is seen in one section. Yet, for many purposes, the generalized concept of a contrast between a substructure and a superstructure, as here defined, is useful. It constitutes one of the major laws of crustal structure.

Law 13. At every point on the land surfaces of the earth, where a superstructure of essentially undisturbed later sediments is absent or locally cut through by erosion, a substructure of rock is shown that bears evidence of having undergone intense deformation and upward movement.

Opinion 9. The continental masses are surviving aggregates of earlier upward deformations, welded into a whole and reduced to a common average level by erosion and sedimentation.

With this opinion in mind, we turn to the next law.

[1] Walther Penck has recently made effective use of the words "Oberbau" and "Unterbau" in this sense. *Die Morphologische Analyse*, Stuttgart, 1924, p. 16.

Parallelism of Coasts and Substructure of Continents.

Law 14. In each of the continents, the larger structural lines marked by folds, foliation, thrust faults, and intrusions, exhibit a noticeable though not invariable parallelism with the borders of the continent.

The wording of this law is taken with a few changes from a paper by R. T. Chamberlin,[2] of which it forms the central theme. A few illustrations taken from it will serve to show the general truth of this law. The present coast of Labrador parallels the trend lines of its pre-Cambrian rocks. The Atlantic and Gulf coasts are accompanied inland by the late Paleozoic folded belts of the Appalachians and Ouachita-Arbuckle Mountains. The general plan of our Appalachian region seems to be repeated on the east side of the northern half of South America.[3] The valleys of the Parana and the Sao Francisco Rivers probably correspond structurally to our "Appalachian Valley" with the essentially pre-Cambrian highlands to the east and a bold plateau escarpment on the west.[4] The lowland belt of the Parana-Sao Francisco Rivers repeats the right-angle bend of the coast at Cabo Frio, as do the ranges nearer the coast, such as the Serra do Mar, Serra da Mantequeira, Serra do Espinhaço, and others. In contrast to the Appalachian region, the latest structural effects of rock folding are pre-Devonian (e.g., along Sao Francisco River).

On the Pacific side, the Cordilleras of North and South America are part of the remarkable belt of orogenic activity which surrounds the Pacific. On both the east and west sides of the southern half of Africa, pre-Cambrian and early Paleozoic folds run parallel to the north-south coasts. The east side of Australia is paralleled by Paleozoic folds and so on.

In a rough way, the great Alpine-Himalayan belt borders the south coasts of Europe and Asia, although, plainly, such a statement is forcing facts somewhat, because, after all, there is a difference between the Mediterranean and Red Seas on the one hand, and the great

[2] R. T. Chamberlin, "The Significance of the Framework of the Continents," *Jour. Geol.*, Vol. 32, 1924, p. 561. See also: "The Intimations of Shell Deformation," *Jour. Geol.*, Vol. 29, 1921, pp. 416-25; "The Wedge Theory of Diastrophism," *Jour. Geol.*, Vol. 33, 1925, pp. 755-92.

[3] E. Suess, *The Face of the Earth* (translated by Sollas and Sollas), Vol. II, pp. 138-9 (E. Suess-DeMargerie, *La Face de la Terre*, Vol. II, pp. 224-6).

[4] This appears generally in the form of a mountain range on hachure maps. See, e.g., Map 107 in the new edition of Stieler's *Atlas of Modern Geography*, Part II, 1925. (Justus Perthes, Gothe.)

ocean basins on the other. And then there are real exceptions, orogenic belts that run across continents, like the Ural Mountains, and others that set forth at right angles to the shore line, like the Paleozoic Sierras of Argentina south of the Rio de la Plata; the Appalachian folds on the coast of Newfoundland; or the great ranges of Burma.

We shall have to say more about these exceptions later on. In spite of them, the law undeniably holds good in the qualified form in which it is here stated. There is, in fact, no reason for surprise over it, if we view it in the light of our opinion. According to it, continents grow by the addition of zones of folding.

But the law of the reversibility of radial crustal movements (law 2, p. 2) suggests that continents may also be diminished by downward movements along their borders. That such loss of areas has taken place on many coasts is evident from the geologic maps. Suess long ago pointed to the contrast between coasts of the "Atlantic" and "Pacific" types.

But even on coasts of the "Atlantic" type, the tendency expressed in law 14 is manifest. Here it seems that the "grain" of the substructure produced by earlier deformations has influenced the trend of the flexures and faults which accompany the downward movement.

We may express this view as:

Opinion 10. The frequent parallelism of modern continental outlines with trend lines of older folding is only in some cases due to the folds actually fashioning the margin. More frequently it appears that later downwarping which created the present continental outline was influenced in its trend by the "grain" of the continents, the trend of folds and foliation, produced by the older deformations.[5]

Geosynclines and Continental Borders. Law 14 was introduced at this point because Chamberlin and others before him, since Dana, have derived from it the opinion that the association of folds and continental borders is necessary and sufficient to explain the origin

[5] The inheritance of later structural and physiographic trend lines from pre-Cambrian times is stressed especially by Ruedemann. See R. Ruedemann, "The Existence and Configuration of pre-Cambrian Continents," *N.Y. State Mus. Bull. 239-40, Seventeenth Ann. Rept. of the Director*, 1920-1921, pp. 67-152. *Am. Jour. Sci.*, 5th ser., Vol. 6, 1923, pp. 1-10. There seems little doubt that Ruedemann's reconstruction of pre-Cambrian structural trend lines is far too generalized. See, e.g., Wm. J. Miller, "Pre-Cambrian Folding in North America," *Bull. Geol. Soc. America*, Vol. 34, 1923, pp. 679-702. Yet Ruedemann has done a real service in setting forth forcibly the principle of inheritance of trend lines.

and location of geosynclines. Along the borders of the continents, sediments are assumed to accumulate in great thickness, the crust being depressed by the load. The presence of the resulting thick sediments in place of the normal crystalline rocks weakens the crust. The topographic difference between the crystalline basement on the continent and its depressed continuation at the bottom of the geosyncline imparts to thick sediments in the latter a "weakness of attitude, a particular border quality."[6]

In focusing attention on this concept of a "weakness of attitude," Chamberlin has made an important contribution to geological thought. We shall return to it at length later. Here we must concern ourselves with the question, did the margins of continents actually provide the conditions which localized the geosynclines? Did the mobile belts of the past lie on the borders of the continents?

Geosynclines and Continental Borders. Throughout the Paleozoic, the Appalachian mobile belt lay west of the hypothetical land "Appalachia." Barrell estimated that the watershed of this hypothetical land "Appalachia" lay about where the one hundred-fathom line of the Atlantic is now,[7] that is, something like one hundred miles east of the shore of New Jersey. Whichever way we may picture to ourselves Appalachia, we cannot avoid the conclusion that much sediment must have been carried eastward to the nearest oceanic shore, as well as westward into the Appalachian geosyncline. But whenever deformation occurred, it was in the belt that lay hundreds of miles inland from the outer border of the continental block and never on the border itself, so far as our records go.

The same is true of the Cretaceous Rocky Mountain geosyncline and of the mountain ranges grown from it. It lies abundantly far from the slope that leads from the continental surface to the ocean bottom to show that it does not owe its existence to the peculiar "border qualities" of this slope.

It is entirely possible to take a broader view of the relations between oceanic and continental areas. T. C. Chamberlin taught that on the earth "the downward movements are unquestionably the primary

[6] R. T. Chamberlin, *op. cit.*, p. 568.

[7] Joseph Barrell, "Upper Devonian Delta of the Appalachian Geosyncline," *Am. Jour. Sci.*, 4th ser., Vol. 37, pp. 248-9.

ones . . . the master movements are the sinkings of the ocean-basins."[8]

In that sense mobile belts may be thought to arise in a broad border zone of indefinite width through the action of crustal stresses controlled by the contrast of ocean floors and continental platforms. This, indeed, comes nearer being a correct representation of R. T. Chamberlin's views. It introduces the idea of crustal stresses arising through the subcrustal processes which lie back of the sinking of the ocean floor. We shall return to this concept later and shall find it of fundamental importance.

In speaking of the factors which localize the geosynclines and with them the folded belts, we can avoid confusion of ideas only by taking the expression "edge of continent" and "border tract" literally.

Fig. 14[9] shows in a generalized way the lines of late Mesozoic and Tertiary orogenesis. Let us ask ourselves sincerely, "Is this the picture we should expect if the master movements of diastrophism were the sinking of the ocean basins and if orogenesis resulted largely from the crowding of the heavier and stronger oceanic segments against the edges of the lighter and weaker continents utilizing the 'weakness of attitude' of the border tract?" It seems impossible to deny that the course of these orogenic belts is contrary to that idea. The borders of the Indian, Atlantic, and Arctic Oceans are singularly unconcerned with the trend lines of the Eurasian ranges. The circum-Pacific belt would give a different picture, it is true. But the view that we question is not concerned with any single unit, such as the Pacific, but with oceanic as against continental segments. As far as the latest orogeny is concerned, of which we have the most complete record, we must answer the above question in the negative, for one hemisphere at any rate.

Although existing information is incomplete we can say confidently that the answer must be equally negative when the hypothesis is tested by the late Paleozoic orogeny. Fig. 15 is here reproduced from a recent paper by Schuchert.[10] It is not intended to be more than a crude

[8] T. C. Chamberlin and R. D. Salisbury, *Geology*, Vol. I (2nd ed.), 1909, p. 545 (1st ed., 1904).

[9] Reproduced from R. Staub, *Der Bewegungsmechanismus der Erde*, Berlin, 1928, Fig. 16, p. 29.

[10] C. Schuchert, "Review of the Late Paleozoic Formations and Faunas, with Special Reference to the Ice-Age of the Middle Permian Times." *Bull. Geol. Soc. America*, Vol. 39, 1928, p. 794, Fig. 2.

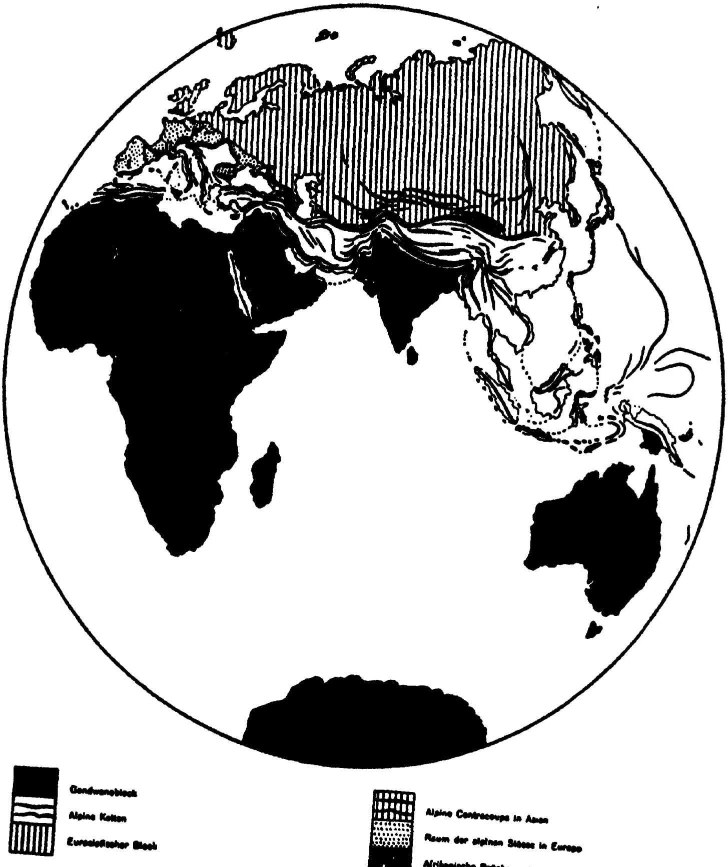


Fig. 14. The axes of late Mesozoic-Tertiary orogeny in the Eastern Hemisphere. (R. Staub, 1928; reproduced from *Der Bewegunsmechanismus der Erde*, by permission of Verlags-buchhandlung Gebrüder Borntraeger.)

sketch of the general location of orogenic movements at the close of the Paleozoic as far as known.

The facts evident from these maps are of sufficient importance to deserve formulation as a law.

Law 15. During any limited unit of post-Algonkian time, small compared with the whole geological record, some orogenic belts lay

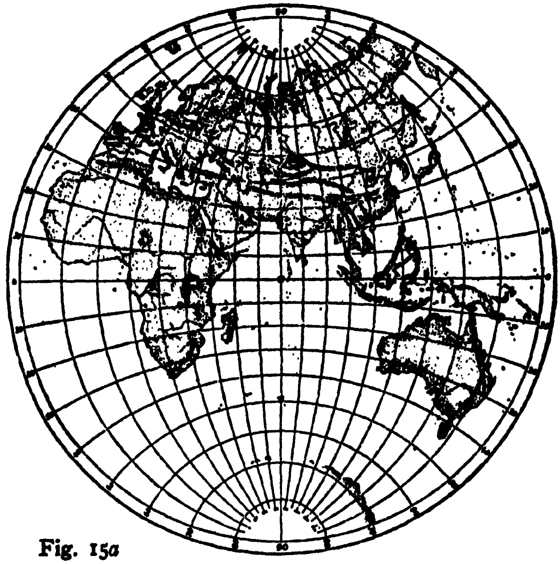


Fig. 15*a*

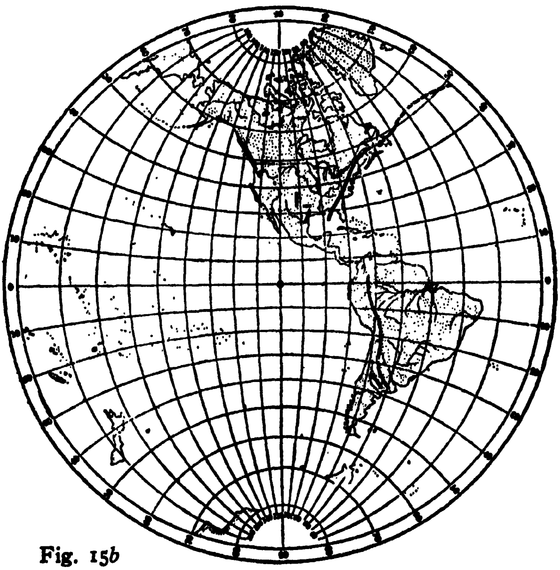


Fig. 15*b*

Figs. 15a and *b*. Belts of orogenic activity of late Paleozoic times (Mississippian to Permian).

(Ch. Schuchert, 1928)

far from the edge of the continental platforms, and always the number of continental shores that were free from orogenic movements was much greater than the number affected by them.

2. Intra-Continental Mobile Belts

The Theory of Continental Drift. The existence of intra-continental orogenic belts is one of the critical facts by which we can judge the applicability of Wegener's interpretation of the dynamics of the crust. According to Wegener's view, the continents float in the heavier substance of the ocean bottom ("sima") as ice floats in water. At times they are free to drift through the rock of the ocean floor. They are suspected of being adrift now. At times again the continental floes become "grounded." Then, while held stationary by friction below, they break down internally along belts of shearing and compression under the impulse of the same gentle pull that before impelled them and afterwards again impels them to drift buoyantly through the yielding sima. If we revert to the comparison with ice floating on water, which is employed by Wegener himself, we have the picture of an ice floe grounded on a sandbank, yielding internally along zones of compression and crushing under the steady gentle pressure of the current (air or water) which presently again will cause it to drift along the surface of the water. The lines of yielding are the orogenic zones. This internal crushing of the continental floes has been called "intra-continental" drift. It would correspond to "intra-ice-floe" drift.

This second word sharply sets forth the physical concept involved. But it is unjust. For Wegener assumes further that at a relatively short distance below the surface, the rock materials of the earth's crust are devoid of all "strength," that is, are unable to resist a change of shape if stress is applied continuously. This one property (not others) they would share with liquids. Both the floating continents and the rock materials of the ocean floor would be plastic and would differ only in the degree of "plasticity," in viscosity.

From the point of view of elastic behavior toward continuous stress,[11] it would be more appropriate to compare the continents

[11] "Rigidity" and "plasticity" may well exist simultaneously in one and the same substance. "Shoemaker's wax, for instance, is a famous example. . . . It is possible to make tuning-forks of it, the free vibrations of which have a frequency sufficiently high to enable them to give out an audible note; the resilience thus indicated im-

with cakes of tar just below the melting point floating in liquid tar of different composition just above the melting point. We must then think of one of these tar floes grounded, say in a shallow pan, and its whole mass subject to a gentle force, for instance, the acceleration imparted to it by rotation of the pan. Although grounded below, the mass would yield in its upper part to this steady force and would wrinkle under the influence of this "intra-tar-floe" drift, the counterpart of the intra-continental drift. The continents are thus pictured as cakes of lighter silicate substance floating on a heavier, less viscous silicate shell. Orogenesis is the wrinkling of the more viscous continental cakes on their margins and internally under the impulse of diminutive differential effects on the floating continents of centrifugal acceleration and of the tides.

Most of us, accustomed to the traditional views of geology, have found it difficult to think through the implications of Wegener's revolutionary premises. We are apt to look to the physicist to tell us whether the premises are qualitatively and quantitatively correct. But the physics of materials is still in its infancy, especially that of materials under high confining pressures. Moreover, even if physicists should deny the correctness of the premises, we might find them in the end indispensable on the basis of geological evidence. Physicists once denied the possibility of more than a few tens of millions of years for the age of the earth. At that time ample evidence had been accumulated by geologists to make their stand against physical opinions determined and practically unanimous. There is no such compelling evidence to drive geologists to Wegener's views. But on the other hand, there is no compelling evidence for any of the other interpretations of crustal deformation.

We might, of course, simply refer to opinion 3 (page 39) and the reasoning on which it is based. If we accept it as true, we eliminate the fundamental concept on which the hypothesis of continental drift is built, and need not concern ourselves further with Wegener's lines of thought. It is better, however, not to be too certain of the

plies rigidity. Yet when one of these forks is left to itself, it gradually flows out under its own weight, until a uniform flat surface has been produced. Hence it has no strength." H. Jeffreys, *The Earth*, Cambridge University Press, 1924, p. 113 (quoting Lord Kelvin, *Baltimore Lectures*, Cambridge University Press, 1904, pp. 9-10).

position we have reached and to think through other points of view to test them for consistency and sufficiency. Wegener's own writings, his book especially, use largely generalized aspects of geographical, biological, paleogeographical, and paleoclimatic data and ideas as supports for his hypothesis.[12] The discussion of orogenesis in the light of his theoretical views is most unsatisfactory. In 1922, E. Argand read an extensive address before the Thirteenth International Geological Congress at Brussels.[13] In this vivid, though involved paper, he gives a bold synthesis of the concrete realities of Eurasian tectonics interpreted in terms of "mobilism" as he calls it, in contrast to the traditional "fixism." His interpretation rests on the two fundamental concepts of Wegener's reasoning. The first is that of continental "floes" of "salic" matter adrift in the "sima"; the second is the essential plastic behavior of all crustal materials under long-continued stress. The systematic application of this idea to continental structure is the specific contribution of Argand's genius. It is difficult to overestimate the importance of the change of mental attitude that is reflected when we begin to speak of the "relative plasticity" of rocks instead of their "relative strength."

It is important to the progress of our thought that we realize that these two concepts are not mutually dependent. One may very well

[12] F. B. Taylor published a theory of continental drift in 1910 in his paper on "Bearing of the Tertiary Mountain Belt on the Origin of the Earth's Plan," *Bull. Geol. Soc. America*, Vol. 21, 1910, p. 179. A bibliography of later papers by Taylor is found in his paper "Correlation of Tertiary Mountain Ranges in the Different Continents," *Bull. Geol. Soc. America*, Vol. 41, 1930, p. 432. Wegener's first publications on continental drift appeared in 1912. A. Wegener, "Die Entstehung der Kontinente," *Petermanns Mitt.*, 1912, pp. 185-95, 253-6, 305-9; also in *Geol. Rundschau*, Vol. 3, 1912, pp. 276-92. The first edition of Wegener's book, *Die Entstehung der Kontinente und Ozeane*, appeared in 1915. An English translation by J. G. A. Skerl, made from the third German edition (1922) appeared in 1924 under the title: *The Origin of Continents and Oceans*, New York (E. P. Dutton & Co.). References to earlier expressions of similar views are found on pages 8 to 9 of the English edition. A good perspective of Wegener's theory, with special emphasis on its bearing on orogenic problems, is given by W. A. J. M. Van Waterschoot van der Gracht, in the *Introduction to the Symposium on the "Theory of Continental Drift,"* published by the American Association of Petroleum Geologists, 1928, pp. 1-75.

[13] Emile Argand, "La tectonique de l'Asie," *Congr. Géol. internat., XIII, 1922, Compt. Rend.*, 1er fasc., pp. 171-329. The best statement of the core of Argand's interpretation of the mechanism of continental deformation is found on pp. 201-3; 279-81; 297-9. Chapter XXXI (pp. 324-8) offers a review of the broader aspects of crustal deformation as seen by Argand. But essential points of theoretical significance are so interwoven with the descriptive part of the paper that a correct understanding of Argand's views is possible only by reading the whole address.

correspond to reality and the other not.[14] At this point of our inquiry we are concerned only with the first of the two basic concepts. Is a drifting of continents necessary or sufficient to account for the presence of intra-continental mobile belts? Before we can attempt to give an answer to this question, we must understand the various ways by which according to Wegener and Argand the plastic continental floes developed zones of folding. Argand distinguishes three types of folded belts:

1. Crustal folds ("plis de fond") (*op. cit.*, p. 216), the broad arching of the continental surface through friction at the base and with the crust in the process of drifting. They involve the greatest expenditure of energy, and the least conspicuous deformation.

2. Marginal folds ("chaînes liminaires"), that is, folds at the prow of the drifting continent (*op. cit.*, p. 296), for instance, the Cordillera of North and South America. The mechanics assumed for these folds are strange indeed. The less plastic mass of the continent is pictured as thrown into folds by the "resistance" of the more plastic substratum. We shall be willing to entertain such seemingly illogical ideas only if the theory of drift as a whole proves to be a real key to the understanding of the continental structure as a whole.

3. Geosynclinal folds ("chaînes géosynclinales") (*op. cit.*, p. 299). For the origin of geosynclinal depressions, Argand has introduced a new hypothesis. He sees in them the result of plastic behavior under tension. As the rising mountain welt is assumed to indicate a thickening of the crust under compression, so the sinking of a furrow is thought to mean a thinning of the "salic" continental mass. A geosyncline, then, would be a zone along which the parts of a continental mass tend to pull apart. When the tension eventually is replaced by compression, the thin, weakened floor of the geosyncline is thrown into wrinkles, the geosynclinal folds.

Now this is the crucial point: However doubtful the physical processes involved may appear to us, we must recognize that the first

[14] This statement is true, although it reveals the eclectic tendencies of our whole effort. Argand denounces eclectic methods in strong terms. He writes "Nous avons repoussé, après examen, toutes les suggestions du vague éclectisme qui eût pu chercher à concilier, dans le demi-jour de combinaisons sans force, ou dans les jeux de bascule d'un scepticisme délicieux, des termes inconciliables. Ces petites habiletés n'ont encore rien fondé, en quelque ordre que ce soit" (*op. cit.*, p. 326). To this the writer would reply that it is not the function of scientific inquiry to "found" anything such as, e.g., a new school of thought, but to discover true relations.

two types of crustal deformation may be conceived directly as a consequence of the fundamental hypothesis of drifting continental floes. But for an understanding of the intra-continental mobile belts, folded geosynclines, the drifting alone is not sufficient. Their explanation requires the introduction of an additional, auxiliary assumption. They are possible only if there is an oscillatory movement of parts of the continental floes. One part must be held by friction while the other drifts off, drawing out the crust thin along the line of parting. Later the straying portion must be held, while the lagging part catches up.

How vital this auxiliary hypothesis is becomes evident when we apply it to the starting condition of Wegener's reasoning. The broad lines of geographical and climatological arguments which give weight to Wegener's interpretations in the minds of geologists, geographers, and climatologists, all converge in the fundamental concept of a parental land mass in which our present continents were originally united. The maps in Fig. 16, reproduced from Wegener's book[15] show this fundamental concept at a glance. These maps, in fact, have done more to attract attention to Wegener's ideas than all the text. The very nature of the evidence adduced demands that the parental continent must have been essentially a unit as late as the end of Paleozoic time. Eliminate this condition and you destroy the power of the hypothesis to give an understanding of the heterogeneous data on which it was conceived.

The Mobile Belts of Wegener's Parent Continent. Taking this parental continent of Wegener's hypothesis, we repeat our question: Is the assumption that this continent drifted sufficient to account for the intra-continental mobile belts that existed on it? The first map of Fig. 16 shows the picture of the parental continent with the chief geosynclinal belts of late Paleozoic times transferred into it as heavy black lines from Schuchert's map reproduced on page 68 of this book. It is understood, of course, that much of the orogeny of later Paleozoic time is as yet unknown. The lines here shown represent, therefore, only a part of the mobile belts of the hypothetical parent continent. We see at once that most of them occupied an intra-continental position. Applying the mechanism provided by Argand's modification of Wegener's theory, we must assume the following

15 Reproduced from A. Wegener, *The Origin of Continents and Oceans*, translated from the third German edition of 1922 by J. G. A. Skerl, 1924, Fig. 1, p. 6.

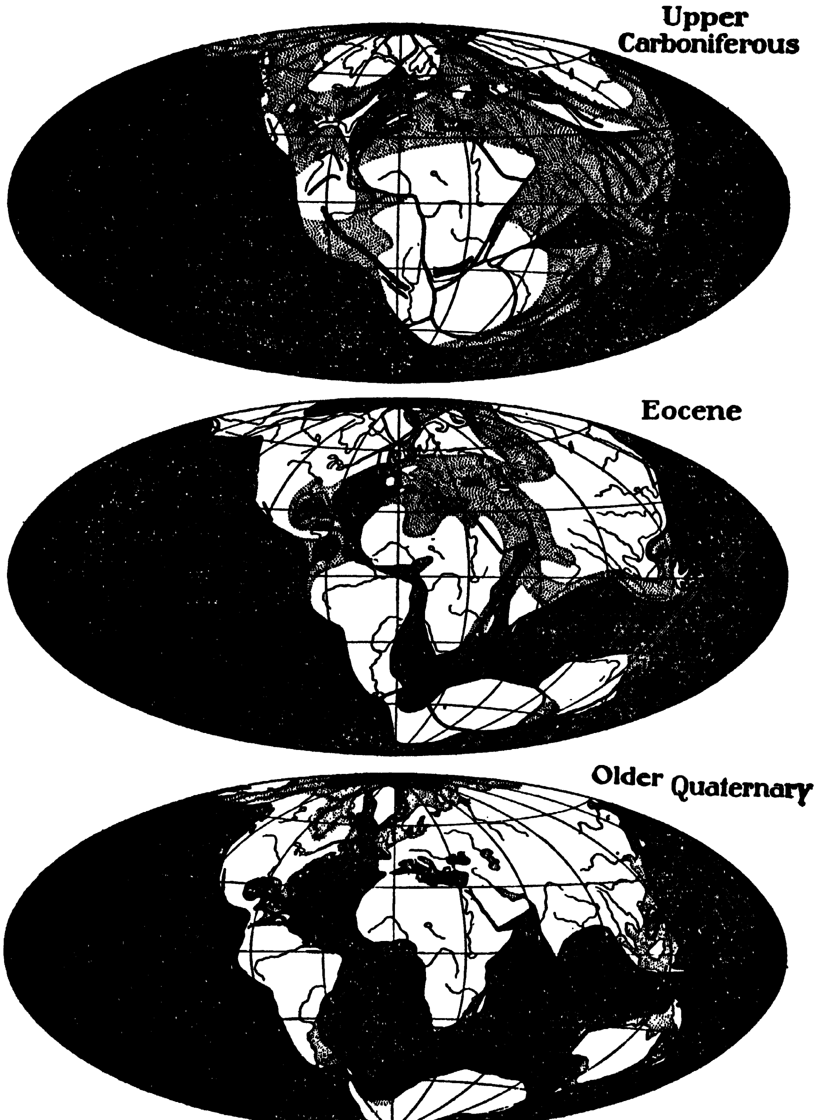


Fig. 16. Reconstruction of the map of the world for three periods according to Wegener's displacement hypothesis.

Lined = ocean; dotted = shallow seas; heavy black lines (added to the uppermost figure by the present writer) = axes of late Paleozoic orogeny (see Fig. 15). Present-day outlines and rivers only for the purpose of identification.

(A. Wegener, 1922; reproduced by permission from *The Origin of Continents and Oceans*, published by E. P. Dutton & Co., Inc.)

events. The geosynclinal belts came into existence when parts of the parental continent began to pull away from the rest. The lines of yielding and pulling-out of the salic crust today are occupied by the belts of thick sediments folded in late Paleozoic time in the Appalachian region, the Hercynian system of Europe, and the belts in central Asia, eastern Australia, South Africa, western South America. Their arrangement would indicate a pulling away in all directions. But the fact that they have undergone intense folding indicates that the reverse movement has taken place repeatedly. Somehow the core must have "caught up" with these deserting elements although they lay around it on all sides. All these reunions need not have all been simultaneous, but they must have occurred repeatedly and in all directions of the compass. More remarkable yet: when the parent continent ultimately split up it was not along these zones but along entirely new lines. This time, however, there was no significant thinning of the salic mass nor vacillating movement that gave rise to folding, for there are nowhere late Paleozoic geosynclinal belts and folds along the new lines of parting, not on the east and west sides of Africa, nor south of India, nor on the north and west sides of Australia. The old geosynclinal belts, however, have not yet ceased functioning. They suffered rejuvenation again in the late Neogene.

Beneath the folded sediments of late Paleozoic age lie the peneplained remnants of still older orogenies, of "Caledonian," Proterozoic, Archean age. The picture here drawn for the late Paleozoic orogeny must not be thought of as exceptional, but must represent the typical process of crustal deformation for the larger part of geological time.

From this hasty sketch it is clear that the fundamental concept of continental drift, with a parent continent tearing along lines of weakness and buckling under the influence of friction is not sufficient to account for the existence of the large intra-continental mobile belts. A special auxiliary cause for the changes of relative speed of drifting must be introduced to account for the folding of the geosynclinal belts. To the writer's mind this is not the sort of clearing perspective that accompanies growing understanding. The central thought is not the master key to the essential doors. It is *not* sufficient to shed light on the most conspicuous feature of the continental masses, the mobile

belts that traverse them.[16] That it is not necessary, will appear from the discussions of the next chapter.

To the writer, then, the conclusion seems inevitable that neither the hypothesis of mobile belts localized along the margins of continents, nor the mechanism of crustal folding furnished by the hypothesis of continental drift, are adequate to account for the actual distribution of folded geosynclinal belts.

[16] Subcrustal flow connected with the disturbance of equilibrium is one of the factors that figures prominently in Argand's interpretation, especially of the arrangement of arcuate mountain folds. It constitutes a second independent auxiliary hypothesis invoked for the explanation of the actual pattern of the folded parts of Eurasia. There is, of course, no limit to the number of auxiliary hypotheses that may be called upon to fit inconvenient facts into a theory which is more plastic than it assumes the earth's crust to be. Argand's characterization of Wegener's theory is not necessarily all praise: ". . . elle n'a pas été réfutée. Il faut avoir longuement cherché des objections, et surtout en avoir trouvé quelques-unes, pour estimer à son prix l'espèce d'immunité qui la distingue, et qui lui vient d'une extrême flexibilité jointe à une grande richesse en tours opératoires. . . . C'est la résistance protéenne d'un univers plastique" (p. 292).

CHAPTER IV

THE PATTERN OF THE MOBILE BELTS

"Nur erst, wenn dir die Form ganz klar ist,
wird dir der Geist klar werden."
Robert Schumann, in *Musikalische Haus- und Lebensregeln.*

1. The Problem

Looking back over the opinions derived in Chapters II and III, we see the reason for grouping laws 9 to 15 together. They comprise a statement of realities which, though not always clearly recognized, seem incompatible with some of the views that are now current concerning the origin of mobile belts.

Most of the fundamental ideas concerning crustal deformation arose ultimately as broad deductive concepts derived from fields of thought outside of geology. Some are based on hypotheses concerning the origin of the solar system—that is, on astronomical data. The classical view of a distinct collapsing crust on a shrinking earth, for instance, rested originally on the Kant-Laplacian nebular hypothesis; it can, of course, also be adapted to the tidal disruption theories of Jeans and Jeffreys. Chamberlin's hypothesis of a compacting earth, without sharply defined crust, is the outcome of his planetesimal theory. Others, for instance those of Bowie and Wegener, were developed primarily on the basis of geodetic hypotheses, Bowie's on the hypothesis of Pratt, and Wegener's (also Joly's) on that of Airy.

In each case the ideas concerning orogenesis appear as broad deductive generalizations into which facts are fitted as well as possible. In this sense their approach to the problem of crustal deformation is diametrically opposed to ours. In these pages we are attempting to derive our views inductively from an analysis of all facts, if possible, following the high example of Chamberlin and Moulton who replaced the deductive generalities of the nebular theorists by inductive analysis of the dynamical properties of the solar system.

For the purposes of our analysis, we may consider the mobile belts as zones of weakness, or, mechanically speaking, as lesions of the earth's surface. Our task is to reconstruct the mechanical causes from their effects. It is, in fact, not essentially different from the homely

task of telling what caused the damage to a broken cement walk or a glass door. The first significant property we observe is the pattern formed by the lines and surfaces of deformation. To define adequately the pattern of the earth's mobile belts in the form of one or several laws must, therefore, be our next step. At no point in this critical analysis will it be more difficult to avoid confusing observation with imagination than here.

In order to be diagnostic of the mechanism that produced it, the pattern of the mobile belts we wish to define must have originated in a sufficiently short time to preclude a disturbing overlap of deformations produced during widely different stages of the dynamic history of the crust. This provision at once limits us to the mobile belts of Cenozoic time in which vertical movements (with or without folding) have taken place recently enough to cause the welts to stand out sharply in the present topography. For older mobile belts which have to be reconstructed on the basis of geological evidence alone, accurate timing cannot be carried out everywhere and information is too incomplete as far as the whole earth is concerned.

For our definition of the pattern of the modern mobile zones we must look, therefore, primarily to hypsometrical and bathymetrical maps of the earth and only secondarily to geological maps. We need the latter because the effects of erosion, and incomplete information and false generalizations in the drawing of contours or hachures on maps, make it difficult to recognize the location and shape of "welts" and "furrows" on topographic maps alone. Generally, a belt that rose dynamically as one "welt" has been resolved into a group of parallel ridges chiselled from the inner structure by erosion. Most "furrows" are filled with sediments or covered with water. Yet, if we remember the inherent uncertainties as to detail, the major features at least of the "welts" now standing on the face of the earth can be made out.

2. The Pattern of Modern Crustal Folds in Detail

The Southern Rocky Mountains. Let us first view the details of the pattern of modern "welts." As before, we must limit ourselves to a few selected illustrations. In Fig. 17, the trend lines of the Southern and Central Rocky Mountains have been drawn to show their pattern. The single range of the Sangre de Cristo Mountains at the southern

end of the system bifurcates in southern Colorado near La Veta Pass. The Wet Mountains, which here appear as the eastern branch, trend on the whole parallel and *en échelon* with the northern Sangre de Cristo Range. Yet as far as the system as a whole is concerned it clearly forms the eastern branch of a Y-shaped fork.[1]

This eastern branch is continued in the Front Range which again lies distinctly *en échelon* with reference to the Wet Mountains. The northern end of this branch bifurcates again. The Laramie Mountains swing off in a graceful curve convex toward the east, with the Medicine Bow Mountains forming the western branch. The western fork of the Y is formed chiefly by the Sawatch Range which starts from the northern end of the Sangre de Cristo Range distinctly *en échelon*. The northern end of the Sawatch Range gives the appearance of a beginning bifurcation. The eastern branch, starting off *en échelon*, is formed by the Park Ranges. A western branch is less clearly shown topographically but is evident on the geological map. Yet it is but a short stump at best with its axis plunging beneath the plains. Fairly in its continuation to the northwest the axis of another welt rises from the plains, that of the Uinta Mountains. The dotted line in Fig. 17 shows the connection which is justified by the geological structure.[2]

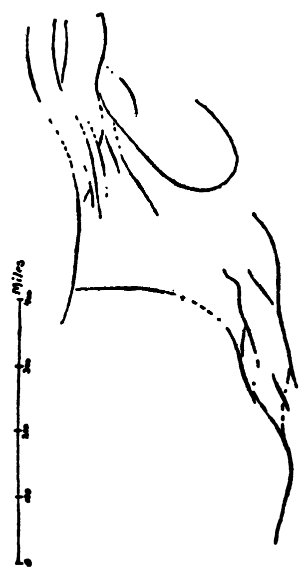


Fig. 17. Diagram showing the structural axes of the southern and middle Rocky Mountains.

In the northern Rockies we see, going still northward, the separate branches of the Teton, Wind River, and Bighorn-Owl-Creek Mountains converging toward one axis which farther north is represented by the Big Belt Mountains. The crystallines of the Beartooth Moun-

[1] R. T. Chamberlin, "The Building of the Colorado Rockies," *Jour. Geol.*, Vol. 27, 1919, pp. 148-9.

[2] See, e.g., W. H. Hobbs, *Earth Evolution and Its Facial Expression*, New York (The Macmillan Company), 1921, p. 140.

tains suggest an outlying curved axis. Farther west, the Wasatch Mountains and the ranges farther east, such as the Caribou Range, the Snake River Mountains, and others, swerve westward and seem to emerge north of the lava flats of the Snake River Desert in such ranges as the Beaverhead and Lost River Mountains.

The interruption of the pattern by downwarps and by concealing sediments and lavas is so obvious that the minimum of hypothetical connections used here and in later examples requires no further justification. As it stands, the region here shown illustrates on a relatively small scale all four types of forms that "welts" may exhibit in ground plan.

Virgation, syntaxis, deflection, linkage. The first is that of a "virgation" of lines of uplift, the "divergent sheaf-like arrangement of several branches," to quote Suess, the author of the term.[3]

The same pattern viewed from the other direction assumes another significance. From the west, the northwest, and the north the lines of uplift draw together, merging finally into one. This converging of separate lines Suess has called "syntaxis."[4] Staub pointed out that Suess uses the term to indicate not merely the close approach of lines but a close approach combined with abrupt change of direction. He suggests that the term "syntaxis" be used to indicate only the crowding together (with or without fusion of several lines). For abrupt turns in the direction of trend of the lines he uses the obvious term "deflection."[5] We shall use the terms in Staub's sense.

In our illustration the double change of trend which creates the arc that leads from the southern Sangre de Cristo into the Uinta Mountains is a fine illustration of deflection. The Bighorn Mountains, of course, represent the extreme. In Fig. 18*a*, *b*, *c*, the three terms are illustrated diagrammatically. Fig. 18*b* introduces an additional concept, that of land completely surrounded by welts as a result of virga-

[3] E. Suess, *The Face of the Earth* (trans. by Sollas and Sollas), Vol. I, p. 275 (E. Suess-DeMargerie, *La Face de la Terre,* Vol. I, p. 356).

[4] *ibid.,* Vol. I, p. 422. Suess' expression is "Schaarung," the trouping together or swinging into line of different units. Sollas adopted the word "syntaxis." The French edition uses "rebroussement."

[5] "Beugung." R. Staub, *Der Bewegungsmechanismus . . . der Erde,* Berlin (Gebr. Borntraeger), 1928, p. 20.

tion with subsequent syntaxis. For such regions Kober[6] has introduced the term "Zwischengebirge,"—"intermontane spaces." In our illustration the Wyoming Basin comes near being a completely enclosed intermontane space.

The last term here illustrated (Fig. 18*c*) describes the abrupt meeting of interfering arcs for which Richthofen has used the word "linkage."[7] It so happens that the Sangre de Cristo-Sawatch-Uinta Mountains arc meets the Wasatch Mountains in a fine illustration of linkage.

It is significant that all these patterns occur here side by side in the southern Rocky Mountains in such a small area. Since all of the lines in Fig. 17 stand for "welts" in the present topography, it is clear that they all suffered upward movement practically simultaneously, at least during the last epoch of deformation.

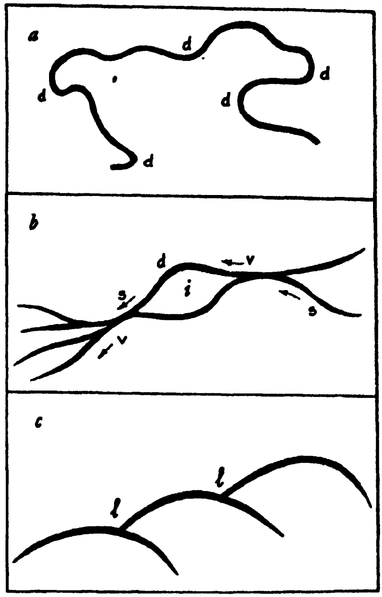


Fig. 18. Diagram showing the characteristic patterns exhibited by welts as seen in ground plan.
d = deflection
i = intermontane space
l = linkage
s = syntaxis
v = virgation

We shall do well to compare a few additional illustrations. A fine example of deflection of two major belts of crustal folds is offered by the chief ranges of Alaska.[8]

[6] Leopold Kober, *Der Bau der Erde*, Berlin (Gebr. Borntraeger), 1921, p. 141. The obvious translation "intermontane space" or region has been used, e.g., by C. R. Longwell, in his review of Kober's *Theory of Orogeny*, in *Bull. Geol. Soc. America*, Vol. 34, 1923, pp. 231-41. In Kober's theory as well as in that of Staub the intermontane spaces play an important rôle.

[7] "Kettung." This was adopted by Suess and substituted for what he had called "Durchschneidung" (intersection). See *op. cit.*, Vol. IV, p. 502 (Suess-DeMargerie, Vol. III, Part 3, p. 1369, "enchaînement").

[8] A. H. Brooks, "Geography and Geology of Alaska," *U.S. Geol. Survey, Prof. Paper 45*, 1906, Pl. VII, opp. p. 28.

The prototype of linkage is found in the island festoons of eastern Asia[9] (Fig. 19).

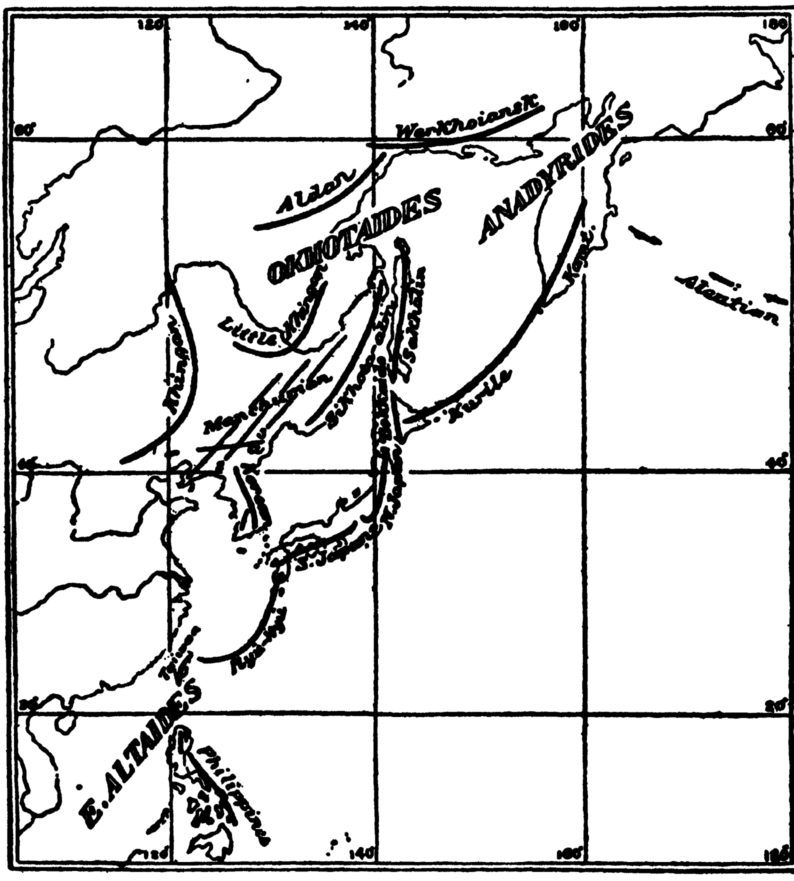


Fig. 19. Tectonic sketch map showing the main orogenic axes of eastern Asia. (B. Koto, 1915)

A sketch taken from Suess' *The Face of the Earth* shows the virgation of the Philippine Islands and the remarkable arc which surrounds the Banda Sea[10] (Fig. 20). This pattern is not unlike that of

[9] B. Koto, "Morphological Summary of Japan and Korea," *Jour. Geol. Soc. Tokyo,* Vol. 22, 1915, p. 117, Fig. 1.

[10] E. Suess, *The Face of the Earth* (trans. by Sollas and Sollas), Vol. III, 1901, Pl. 11, p. 235.

Fig. 20. Tectonic sketch map showing the main orogenic axes of the Philippines and the Sunda archipelago.

(E. Suess, 1901; reproduced by permission of the Oxford University Press from *The Face of the Earth*, Sollas and Sollas translation.)

the part of the Rocky Mountains shown in Fig. 17, a similarity which has been emphasized by Hobbs.[11] It is highly probable that the pattern includes one or several cases of linkage which were omitted by the cautious hand of the master. This occurrence of all types of juncture of crustal folds in a relatively narrow space seems of special interest.

[11] *op. cit.*, pp. 139–43.

That they are found alike in the heart of a continent and on the ocean floor is a further illustration of law 6 (p. 14).

Finally we turn to a diagram of Kober's, which serves well to illustrate the abrupt deflections and the repeated syntaxes of the Alpine system of southern Europe and western Asia, although a few of the arrows and letters represent hypothetical interpretations which we need not accept (Fig. 21).[12]

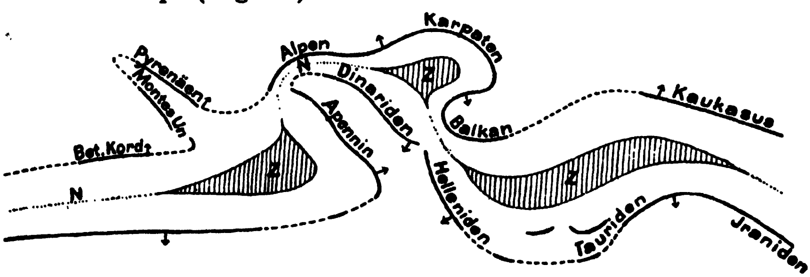


Fig. 21. Tectonic diagram showing the units of the Alpine mountain system of the Mediterranean region, as interpreted by L. Kober.
$Z =$ "Zwischengebirge," i.e. intermontane areas; $N =$ "Narben" ("scars").

We may now summarize our findings as:

Law 16. Viewed in detail, the pattern of the crustal folds is characterized by deflections, by virgation and syntaxis, and by linkage of individual lines.

These patterns are seen alike whether the foundation is on the ocean floor or on the continental platforms (law 6).

Are these details of the pattern of crustal folds sufficiently specific for an analysis of the underlying mechanism?

"Tectonique en mouvement." Again we must turn our attention to the theory of continental drift. With it Wegener has introduced a momentous change in viewing the lines on the face of the earth. He sees all lines as instantaneous pictures of essentially free and continuous movements of the viscous materials of the earth's crust. This is what Argand calls "tectonique en mouvement." Those who accept it look at the fine hairpin curve of the Banda arc and the confusion of islands and deeps[13] northwest of the Australia-New Guinea shelf,

[12] Leopold Kober, *Der Bau der Erde*, Berlin (Gebr. Borntraeger), 1921, p. 140, Fig. 26.

[13] See, e.g., G. A. F. Molengraaff, "Modern Deep-Sea Research in the East Indian Archipelago," *Geog. Jour.*, 1921, pp. 95-121.

and see the result of a gigantic churning. "The extremely active manner in which New Guinea has quite recently pressed, and possibly is still now boring, to the north into the great Soenda festoons, is so obvious that *the fact* cannot be denied by any one who is really familiar with these regions, regardless of its causal explanation. This is the reason why the Dutch geologists (Molengraaff, Brouwer, Wing, Easton), who worked in the East Indies, are invariably favorably inclined to Wegener's hypothesis. Without knowing why, we *see* that New Guinea drifts violently to the north."[14]

Now unquestionably these geologists did not actually *see* New Guinea move. All they saw was a pattern that looks strikingly *as if* produced by an aggressive New Guinea. Only the statement preceded by "as if" is a "fact." Not the statement without the "if," as we read it in the above quotation. It is one of the tricks of the human mind to suppress the inconvenient little words "as if."[15] The essence of the hypothesis of the "stirring" of the East Indian Archipelago lies in the supposed effect of the rigid body of New Guinea on the folds it deflects. The same essential concept we find again in Staub's interpretation.[16] Deflection results when an arc of crustal folds meets a rigid obstacle to which it has to fit itself or about which it is forced to swerve. Here, however, the advancing fold, apparently thought of as something like a wave, is the active agent. Just as van der Gracht, Molengraaff, Brouwer, and others are influenced by their experience in the Moluccas, so Staub's is colored by his intimate knowledge of the Alps. There one can see the Hercynian masses of Iberia, and of Bohemia standing in strategic places, "obviously" deflecting the Alpine trendlines.[17]

But in front of the sharp curve of the Bighorn Mountains we look in vain for a counterpart of New Guinea. Perhaps we should not

[14] W. A. J. M. Van Waterschoot van der Gracht, *The Problem of Continental Drift,* symposium on the theory of continental drift, published by the American Association of Petroleum Geologists, Tulsa, 1928, p. 57. (The italics are the present writer's.)

[15] Hans Vaihinger, *Die Philosophie des als ob,* 5. u. 6. Auflage, Leipzig (F. Meiner), 1920. Translated by C. K. Ogden, New York (Harcourt, Brace & Co.), 1925.

[16] *op. cit.,* p. 20.

[17] A. Wegener, *The Origin of Continents and Oceans,* New York, 1925, p. 183.

be looking for it since we are here in the midst of a continent where such viscous flow lines are not to be expected. As we have emphasized repeatedly, law 6 is a strong argument against the very basis of Wegener's theory.

Similarly at the points of such strong deflections as we see in the Alaskan chains or in the Sangre de Cristo-Uinta arc, we look in vain for "obvious" obstacles that "explain" the deflection. Of course we can place an imaginary one at each point where needed. But that clearly would be doing violence to observational data.

The linked island festoons of eastern Asia, Wegener considers "as marginal ranges, which, by the westerly drift of the continental masses, become separated from them, because those festoons remain attached to the deeply solidified ancient floor of the sea. The younger and more mobile ocean floor crops out in a window-like fashion between them and the continental margin."

To get a correct picture of the mechanism involved in this interpretation we must think, according to Wegener, of a rubber sheet tacked down along one end at roughly equidistant points and pulled at the other end. The edge of the rubber sheet between the fixed points is pulled forward, forming the point of "linkage." Opposite the tacks the rubber tears, leaving the spreading gaps which would correspond to the South Chinese, East Chinese, Japanese, Okhotsk, and Bering Seas.

This is one of the most striking examples of the art of the "tectonique en mouvement." Even in its purely formal aspect this interpretation neglects essential parts of the pattern. The narrow, long, high character of the "welts," as we call them, is continued in each case back of the linkage, as in Sakhalin, Kamchatka, and in the Aleutian Range which swings around into the Alaskan Range. Furthermore, without doubt arcuate mountain belts identical in form and linkage to the island arcs lie inland such as the Sikhota Alin, Stanovoi, and the Verkhoyansk-Kolyma Mountain arc. Finally, the continuity of the mountain belts of the island festoons with the whole circum-Pacific belt of mountains is an outstanding property which is not considered in an interpretation that treats them as inert fragments of a continental floe. The inaccuracy of this treatment becomes obvious when the structure of the island arcs is taken into consideration. The

Alaskan peninsula is a more or less folded and intruded mountain belt, as certainly a tectonically defined unit as any.[18]

The same is, of course, true on a larger scale of the Japanese islands. To speak of them as merely detached portions of the continent is nothing less than a suppression of essential fact. The existence in these island festoons of all the phenomena of deformation and intrusion associated everywhere with mobile belts does not follow from Wegener's premises. It requires special provisions, auxiliary assumptions. The paragraph which van der Gracht has recently devoted to such possible auxiliary hypotheses is instructive.[19] It betrays the insufficiency of the original concept.

The attempts of the Wegener school are based on assumptions which are incompatible with law 16. They treat as different, things which seem obviously of one kind. Since the writer is convinced that laws 6 and 16 are essentially true, he cannot accept the constructions of this type of "tectonique en mouvement" as usable.

Interpretation. Taking, then, the outer crust to be essentially strong throughout, outside the mobile belts, we must now ask ourselves whether the details of the pattern of the crustal folds are found characteristically associated with a specific mechanical process. They are. Virgation, syntaxis, abrupt deflections and linkage, all are seen wherever fractures cross an asphalt or a concrete pavement, or a coating of varnish or plaster. Suess[20] pointed out this analogy in the last volume of his *The Face of the Earth.* His photographs of fractures observed on asphalt pavements are here reproduced as line drawings (Fig. 22).[21] At *a* in the right hand figure we see a good example of the sharp-angled meeting of the two arcs to which Suess confined his use of the word "syntaxis." North of *F* is a fine arc of virgation while the four arcs to the south all meet in linkage. In larger fracture zones virgation and syntaxis frequently produce a line of fragments com-

[18] See, e.g., Wallace W. Atwood, "Geology and Mineral Resources of Parts of the Alaska Peninsula," *U.S. Geol. Survey, Bull. 467,* 1911, or especially such sections as Figs. 10 and 11 (pp. 102-3) in G. C. Martin and F. J. Katz, "A Geologic Reconnaissance of the Iliamna Region, Alaska," *U.S. Geol. Survey, Bull. 485,* 1912.

[19] Van der Gracht, *op. cit.,* p. 57.

[20] E. Suess, *The Face of the Earth* (trans. by Sollas and Sollas), Vol. IV, pp. 503-5. The figures of the plate in the German edition (Vol. III, Part 2, Pl. xx), are here reproduced from the French edition, Vol. III, Part 4, p. 1372, Figs. 310 and 311.

[21] Reproduced from the French edition, Vol. III, Part 4, Figs. 310 and 311, p. 1372; E. Suess, *Das Antlitz der Erde,* Vol. III, 1909, Part 2, Pl. xx.

pletely surrounded by cracks, the equivalents of "intermontane spaces."

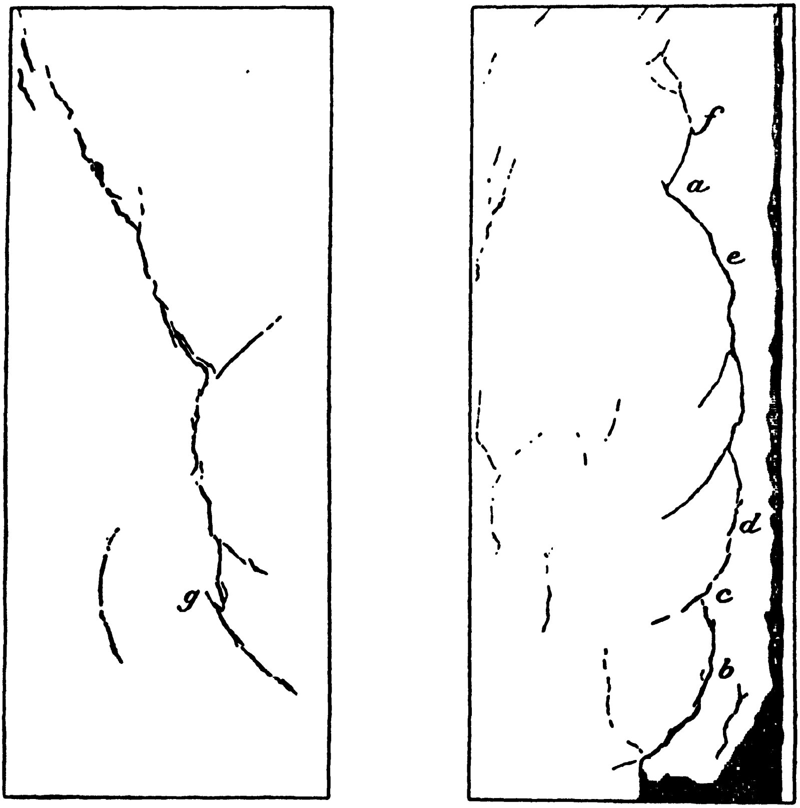


Fig. 22. Cracks in asphalt, photographed by E. Suess.
(After E. Suess, 1909; reproduced from E. Suess-DeMargerie, *La Face de la Terre* by permission of G. Freytag A. G.)

There can be no doubt that tensional stresses are sufficient to produce fractures that show all the details of the pattern exhibited by crustal folds. Let us disregard for the moment the fact that tensional stresses will produce fractures instead of welts. Tension may be sufficient to produce the diagnostic properties of the pattern of crustal folds; yet the question remains, is it necessary, or can identical patterns be produced by compression?

Unfortunately, an answer to this second question is not easy to find. Our daily experience brings us into contact with the effects of tensional stresses everywhere. Comparable effects of compression affecting relatively thin expanses of a material are rarely seen, such as folds of sagging snow on a sloping roof, or thrust faults in the dry snow that piles up in front of a snow shovel. The latter do not concern us here, and the former are a closely packed system of essentially parallel wrinkles.

From the relatively few published experiments it is at least clear that curved folds do not form as readily as curved fractures. Hobbs,[22] for instance, used a triangular frame, exerting pressure on two sides of an equilateral triangle to create arcs of folds. Chamberlin and Shepard[23] produced arcuate folds by pushing one or two jackscrews against isolated points of a broad front of plastic matter. In an experiment with his jacks, a linkage of two arcs was produced. Yet such experiments fail to appear directly applicable to the earth's crustal folds. One wonders what in nature takes the place of the jacks which move actively against an inert mass; or what corresponds in nature to the active sides of Hobbs' triangular frame. The real difficulty in the application of such experiments to the earth's crustal folds lies in the necessary contrast of unyielding stronger masses and the yielding normal surface. As far as our observation goes, a few miles beneath the surface all rock materials, for instance, within and without the Rocky Mountain belt, are crystallines. Why should one part be strong and another sufficiently mobile to fold? There is certainly no obvious group of strong bodies to which the capricious deflections of the arcuate folds of the southern part of the Rocky Mountain system could be referred. Somehow the parallel between such experiments as quoted above and the pattern of crustal folds is not yet satisfactory.

Unquestionably the mechanism of folding of thin sheets has not been studied adequately. Yet we are probably justified in formulating this opinion:

Opinion 11. As far as inadequate observational data permit any judgment at all, the characteristic details of the pattern of the crustal

[22] William H. Hobbs, "Mechanics of Formation of Arcuate Mountains," *Jour. Geol.*, Vol. 22, 1914, pp. 88-90.

[23] R. T. Chamberlin and F. P. Shepard, "Some Experiments in Folding." *Jour. Geol.*, Vol. 31, 1923, pp. 493-4.

folds, especially linkage and syntaxis, form more readily in fractures produced by tension than in the folding of thin sheets by compression.

3. The Pattern of Modern Crustal Folds as a Whole[24]

Young folded mountains. Turning now to the pattern of modern crustal folds as a whole, we find that the relatively narrow belts to which the crustal folds are confined (law 5) are not scattered at random over the face of the earth. In spite of interruptions, *en échelon* arrangements and deflections, the belts viewed as a whole form a very few essentially continuous bands that run across large parts of the surface of the globe. Suess was the first, in his *Das Antlitz der Erde,* to demonstrate the essential continuity of the belts of young folded mountains in both the old and the new world, giving precision to more or less vague conceptions that date back to Buffon and A. von Humboldt. The first graphical representation of this knowledge seems to be the small map of the young folded mountains in the second volume of Neumayr's *Erdgeschichte* (1887).[25] It showed the well known belt encircling the Pacific and departing from it at the Sunda Isles, that other belt which swings into an east-west direction in eastern Tibet and thence extends through the Himalaya Mountains, Persia, Asia Minor, and the Mediterranean countries to the western end of the Atlas Mountains. Within the belts shown on that map lie the greatest crustal folds of the present earth. But by no means *all* crustal folds.

Geosynclines of Mesozoic-Cenozoic time. In 1900 Haug published a paper of fundamental importance on the geosynclines of Mesozoic and Cenozoic time.[26] His map, redrawn on Lambert's azimuthal projection, is here reproduced in Fig. 23.[27] For the stratigraphic facts on which it is based the reader is referred to the original.

As was to be expected according to law 5, the belts of intense orogenic movements of late Mesozoic and Cenozoic time are identical with the most important of these geosynclinal belts. Fig. 23 shows,

[24] Walter H. Bucher, "The Pattern of the Earth's Mobile Belts," *Jour. Geol.,* Vol. 32, 1924, pp. 265-90.

[25] Melchior Neumayr, *Erdgeschichte*, Vol. II, 2nd ed., 1905, p. 481.

[26] Émile Haug, "Les géosynclinaux et les aires continentales, contribution à l'étude des transgressions et des régressions marines," *Bull. Soc. Géol. France,* 3e sér., Vol. 28, 1900, pp. 617-711.

[27] Reproduced from Walter H. Bucher, "The Pattern of the Earth's Mobile Belts," *Jour. Geol.,* Vol. 32, 1924, p. 271, Fig. 2.

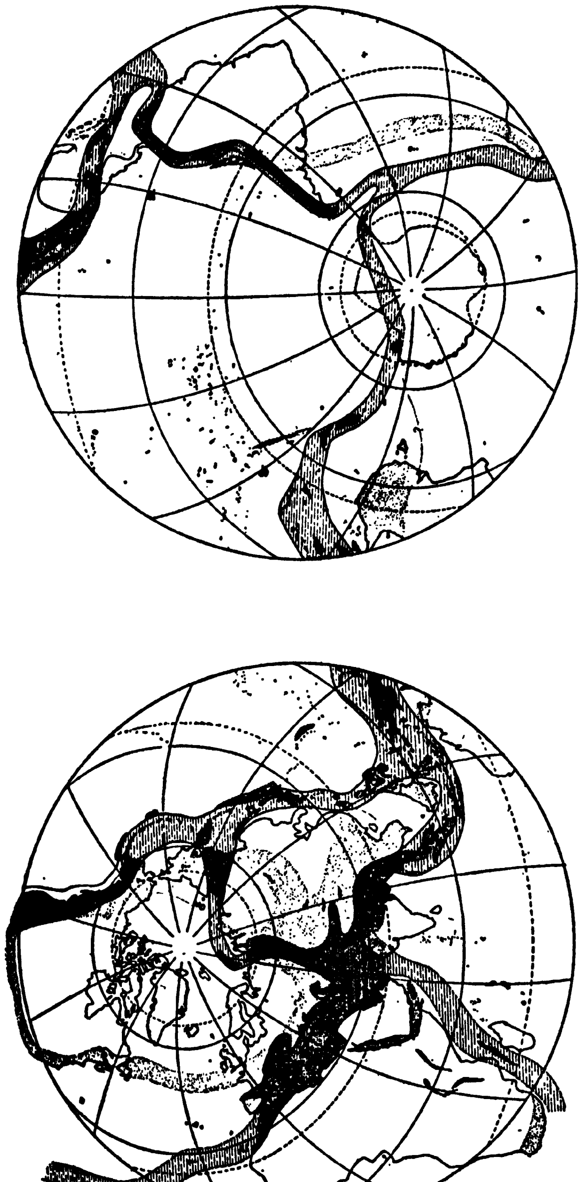


Fig. 23. Map of the earth, showing mobile belts.

Horizontal shading: Haug's reconstruction of the geosynclinal belts of the Mesozoic and early Tertiary (here transferred to Lambert's aximuthal projection). Hypothetical connections of these belts are shown by broken lines. *Stippling:* The main areas over which sediments of unusual thickness were laid down during the later Paleozoic. *Vertical shading:* A number of modern troughs, filled and unfilled, which have existed since the later Tertiary. (The last two added by the writer.)

however, that additional geosynclinal belts existed in Mesozoic time and even down to the present in part, along which no important orogenic movements took place. One of these runs north from the Caspian Sea and fits into the picture the old seaways in the longitude of the Ural Mountains. The other runs south from the Arabian Gulf and includes the old Jurassic trough between Madagascar and the mainland of Africa.[28] It should be noted, especially, that the relatively young meridional belt of depressions which includes the African rift valleys roughly parallels this partly hypothetical zone and suggests an organic connection of this remarkable fracture zone with the major pattern of geosynclines.

The stratigraphic study of geosynclines reveals thus a more complicated pattern than that of the young folded mountains, a fact which requires explanation.

Rejuvenated welts. Returning to the immediate objects of this discussion, we note that the pattern of modern welts includes many in which little or no folding took place in Mesozoic and Cenozoic time, welts of relatively moderate elevation which merely suffered "rejuvenation" recently enough to still rise topographically above the surrounding levels of the earth's surface.

Students in American universities have long been taught to regard the renewed uplift of the Appalachian belt as an important diastrophic event of Cenozoic time. Schuchert, correspondingly, gives in his valuable text-books of *Historical Geology* a map[29] on which, in addition to the belts of folding, a number of older mountain belts are shown which suffered vertical uplift during the Cenozoic, such as the Appalachians, the Scandinavian mountains, and those of eastern Australia.

This map comes nearer giving a picture of the active welts of Cenozoic time. But it is still quite incomplete.

Northeast of the great welt of the Tian-shan we miss the ranges that surround the Dsungarian Gate; the great mountain knot which

[28] For an instructive map, drawn without any preconceptions concerning orogenic hypotheses, see the map accompanying: V. Uhlig, "Die marinen Reiche des Jura und der Unterkreide," *Mitt. Geol. Ges. Wien,* Vol. 4, 1911, pp. 329-448.

[29] Charles Schuchert, *Historical Geology,* 2nd ed., New York, 1924, Fig. 207, p. 609; *Outlines of Historical Geology,* 2nd ed., New York, 1931, Fig. 122, p. 260.

connects the diverging Altai, Tannu-ola, and West Sayan Mountains; the Baikal Mountains and the Transbaikal ranges that lead over to the southern arc of the Stanovoi Mountains (Aldan Mountains); finally, the long and little known ranges of northeastern Siberia, the one leading toward the Arctic shore east of the Lena River (Verkhoyansk Mountains), the other into Anadyr, where on the other side of the Bering Strait, the Endicott Mountain axis abuts against the northeast shore of Kotzebue Sound.[30]

The Ural Mountains and the Appalachians. In the heart of Eurasia we miss above all the low but long continued Ural Mountains. With a length of about 1,430 miles (2,300 kilometers), from the Konstantinov Kamen (68° 29′ N.) to the south end of the Mugojar Hills (49° N.),[31] it rivals the Appalachian folded belt with its 1,500 miles length from central Alabama to New Brunswick in Canada.[32] As in our Appalachians, the truly mountainous part, in which we are for the present interested, is narrow, with a maximum of 70 miles in the south and an average of 50 miles and less in the north. The greatest width of our southern Appalachian Mountains is about 70 miles in western North Carolina. If for the moment we turn to the folded belt as a whole, we find it in each case much wider than the present mountain belt, and again of comparable dimensions. According to the International Geological Map of Europe, the folded belt in the Urals, in 53° northern latitude, is about 260 miles wide (about 415 kilometers). In 63° latitude its exposed width has dwindled to 93 miles (150 kilometers). According to Keith,[33] the strongly folded belt in Tennessee, Georgia, and the Carolinas has an exposed width across the strike of 270 miles, and in Quebec, Maine, and New Brunswick its width is practically the same. "Between these maxima at the north and south the Cretaceous transgression reduced the visible width of the belt to about 80 miles near the Hudson." The elevations also are

[30] A. H. Brooks, "The Geography and Geology of Alaska," *U.S. Geol. Survey, Prof. Paper 45,* 1906, Pl. VII, opp. p. 28.
[31] Serge von Bubnoff, *Geologie von Europe,* Vol. I, 1926, p. 71.
[32] Arthur Keith, "Outlines of Appalachian Structure," *Bull. Geol. Soc. America,* Vol. 34, 1923, p. 311.
[33] *op. cit.,* p. 312.

comparable; the highest peak[84] in the northern Urals, Toll-poz-iz, is 5,537 feet; a few others are above 5,000, as Sablya 5,402 feet, Konzhakovski Kamen 5,225 feet. North and west of Ekaterinburg the Urals lose their character as a mountainous country. In the southern part again occasional peaks rise above 5,000 feet, Yaman-tau to 5,395 feet, Iremel to 5,245 feet. In our northern Appalachians, similarly, few areas rise above 4,000 feet in the Green and White Mountains, and only a very few isolated peaks rise above 5,000 feet, as Mt. Katahdin 5,385 feet and Mt. Washington in the White Mountains, 6,293 feet. In eastern Pennsylvania the belt loses its character as a mountain region for a distance. Then in the southern Appalachians larger areas lie above 4,000 feet, and peaks rise like Spruce Knob, West Virginia, 4,860 feet, Mt. Rogers, Virginia, 5,720 feet, Clingmans Dome, on the Tennessee-North Carolina border, 6,617 feet, and Mt. Mitchell, the highest, 6,710 feet.

This rather long digression on what are after all only superficial externals of the appearance of the two mountain belts is inserted to assign a proper place to these two regions. In both the chief epoch of folding occurred in the later Paleozoic. Then they were elements of first importance in the pattern of crustal folds. The late revival of uplift which has given them a place as "welts" in the pattern of crustal folds, has been very moderate. We get an idea of the form of the late Cenozoic uplift from Hayes and Campbell's map[85] showing the elevation of the older (post-Cretaceous) peneplain in the southern Appalachians. The three- and four-thousand-foot contours are elongated and represent a true "welt," in the broad sense in which this term is used.

Similarly, upwarped peneplains are reported from the Urals.[86] The height and active dissection of such belts of Paleozoic folding are,

[84] Elevations taken from Bartholomew's *The Times Atlas*, Pl. XLV. Those for the United States with one exception from Pls. LXXXVI and XCIII.

[85] H. W. Hayes and M. R. Campbell, "Map of the Southern Appalachians showing the Deformed Cretaceous Peneplain," in "Geomorphology of the Southern Appalachians," *Nat. Geog. Mag.*, Vol. 6, 1894, pp. 63-126.

[86] Serge von Bubnoff, *op. cit.*, p. 106. See also the fine illustrations of remnants of peneplains on Pl. II, Fig. 2, and Pl. III, Figs. 1 and 2 of von Bubnoff's book.

of course, sufficient evidence of relatively recent uplift.[37] Since both the Urals and the Appalachians are today lowly yet conspicuous parts of the "welts" of the earth's surface, whatever origin we ultimately assign to the pattern of the orogenic belts, they must be included in the pattern. In contrast to the bolder welts of our western mountains or the Alpine system of Eurasia, in which later sediments were intensely folded in the course of their formation, we may refer to the Urals and the Appalachians and similar mountain systems as "rejuvenated welts." We shall purposely leave this term purely descriptive, for the present. As in the case of the general term "welt," we imply no mechanism in its formation. The structural differences and their interpretation will be discussed later.

Unlike the Appalachians, however, the belt of which the Ural Mountains are a part has been one of the major seaways during the whole of Mesozoic and Cenozoic time.

Other rejuvenated welts. As our picture of the pattern of modern "welts" must include the rejuvenated welts, if we want to keep ourselves free from arbitrary distinctions, we will do well to recall other examples, e.g.: Far in the north the northernmost mountain range of the earth, the United States Mountains, extends from Cape Morris Jessup at the north end of Greenland westward into Grant and Grinnell lands, with peaks up to 8,000 feet high.[38] In passing, we may note that in the United States Mountains Paleozoic rocks appear to be folded and thrust faulted, chiefly in Caledonian time. But rocks even of Pennsylvanian age show dislocations that point to later disturbances. Here as in the other "older" mobile belts, this existence of mountainous elevations demonstrates recent upward movements which rejuvenated the welts.

To the southeast lies the long and low "welt" of the highlands of Norway, with its old land surfaces bowed up so as to carry but small areas above 5,000 feet and only isolated peaks above 8,000 feet (Galdhöppiggen, 8,332 feet).

[37] Walther Penck, *Die morphologische Analyse*, 1924.

[38] E. Suess-DeMargerie, *La Face de la Terre*, Vol. III, Part 2, pp. 927-31. See also C. Schuchert, "Sites and Nature of the North American Geosynclines," *Bull. Geol. Soc. America*, Vol. 34, p. 193.

Going into central and southern Europe, we find smaller scattered welts of similar character. Among the southern continents, Australia possesses in the "Australian Alps" of Victoria and their continuation north along the east shore, through New South Wales and Queensland, crustal folds entirely comparable to the Urals and the Appalachians. (Small areas above 5,000 feet, isolated peaks above 6,000 feet—e.g., Mt. Bogong 6,508 feet.) Still lower and yet conspicuous in its setting of lowlands on all sides rises the Flinders Range in South Australia.

In South America, we recognize on the map the ranges that center about Rio de Janeiro, of which we have spoken before.

Island welts. There still remain the island groups to be considered. The great arcs of the western Pacific are generally recognized as an integral part of the circum-Pacific orogenic belt. From the purely topographic point of view which we are here following, they are. But the phenomena of folding and intrusion, to which we shall turn later, are so widely distributed at many points within these islands that even in a narrower sense they have to be counted with the typical orogenic belts.

Less than 250 miles off the center of the west coast of British India begins a nearly straight chain of coral islands famous for its atolls—a fine illustration of a case in which coral growth has projected the contour of a submerged mountain range on the surface of the ocean.[39] Separated by two deep channels, the Laccadive, Maldive, and Chagos Islands form a line 1,500 miles long (2,400 kilometers). The widest and deepest channel, between the Maldive Islands and the Chagos Archipelago, is neither wider nor deeper than the interruption by the Black Sea of the Caucasus-Balkan line (of similar length between Baku and Belgrad).[40]

[39] E. Suess, *The Face of the Earth* (trans. by Sollas and Sollas), Vol. II, p. 320.

[40] Jumrukcal Peak in the High Balkan is 9,465 feet high; the Yaila Mountains in the Crimea rise to 5,500 feet; the distance between the two is about 500 miles. The Black Sea drops to 5,000 feet on the line connecting them, that is, there is a depression between these highest peaks on the Black Sea amounting to 15,000 feet. The distance between the outermost islands of the Maldive Islands and the Chagos Archipelago is also about 500 miles. The deepest point recorded on the 1925 edition of *Stieler's Atlas*, the newest map of the Indian Ocean available to the writer at the moment, is 3,899 meters or 12,800 feet.

In length, this submerged mountain system equals our Appalachians and the Urals; its height of 10,000 to 12,000 feet above the surrounding ocean bottom makes it comparable to the Sierra Nevada-Cascades ranges of similar length.

Nothing is known of its structure. But it certainly is one of the great mountain ranges on the earth. Yet it has fared worse than the Ural Mountains in the way it has been left out of consideration in the discussion of orogeny. Like the Urals, it runs north-south, which in this part of the world is disconcerting. On the map which accompanies Staub's *Bewegungsmechanismus der Erde* (1928) it appears as a narrow long block bounded by normal fractures and according to the label it results from the fracturing of the rigid plate south of the Alpine system ("Zersplitterung der starren Schollen"). With its straight boundaries, narrow outline, and great height, it would stand unique on the earth but for one other example of the same hypothetical "Zersplitterung" of which even less is known as to form and height. This is the "Whale Ridge" that extends seaward between Cape Frio of the west coast of Africa and Gough Island, in the southern Atlantic Ocean. It is the arbitrary introduction of such purely imaginary distinctions which robs of conviction the ultimate synthesis of Staub and others. A range fifteen hundred miles long and over two miles high is a bona fide mountain range and not a fragment of a fractured plate.[41]

The central massif of Madagascar rises rather abruptly above the wide lowlands on the west and the narrow ones of the east coast. Over nine hundred miles long and one hundred to one hundred and fifty miles wide, it reaches in rather large areas an elevation above five thousand feet, surmounted by volcanoes. The inner structure of the metamorphics that constitute this central axis and outlying parts seems to differ decidedly from the outline, and the trend of the axes of folding seems nearer east-west than north-south.[42] The modern

[41] The analogy with the fractured masses of Africa and India on which Staub and others since Suess have based their interpretations, applies only to the direction of the fairly straight boundaries which have been interpreted as fault lines. It does not apply to the obvious "welt" character of these large topographic forms.

[42] Paul Lemoine, "Madagascar," *Handbuch d. regionalen Geologie*, Heft 6, Heidelberg, 1911. No newer literature is available to the writer at the moment.

topographic axis is the result of relatively recent uplift. As in all sharp uplifts, the straight edge of the east coast has been interpreted as a fault line and may very well be one. Fracturing commonly accompanies deformation, but here as in all similar cases the fracture does not make the uplift. The age of the crystallines is unknown. They may be pre-Cambrian or early Paleozoic. It seems that Pennsylvanian perhaps and certainly Permian beds lie unconformably on them.[43]

In the broad sense in which the word is here used we must list the central massif of Madagascar among our recent crustal folds. A bathymetric map of the Indian Ocean shows that this axis is continued northeastward in several island groups, of which the Seychelles are the northernmost. It is significant that the Seychelle Islands consist of masses "of granite emerging from a vast basin of coral growths."[44]

A fine submerged mountain arc begins at the Seychelles, with its convexity directed eastward. It ends at the islands Mauritius and Réunion, of volcanic origin. The details of its form are not clear. Yet the long and narrow outline and the elevation above the deep sea seem to place it on an equal basis with other largely submerged arcs, as, for instance, that of the Ladrone Islands in the Pacific.

The pattern defined. This may end our survey of the larger crustal folds of the modern face of the earth. We have not listed all. Smaller ones and perhaps one or another larger one has been omitted. Whatever view we may develop of the nature of the pattern of the crustal folds, it must include the existence of relatively few scattered outlying "welts."

The lines of welts are not continuous across the continents. And yet they visibly group themselves into a larger design, the pattern we are trying to define. We shall formulate it as law 17*a*.[45]

[43] Paul Lemoine, "Madagascar," *Handbuch d. regionalen Geologie,* Heft 6, p. 4.

[44] E. Suess, *The Face of the Earth* (trans. by Sollas and Sollas), Vol. I, p. 417 (E. Suess-DeMargerie, Vol. I, p. 531).

[45] The writer realizes that such a statement of specific fact is not a "law." Yet he has decided to let it appear under this designation to secure for it a proper place among the generalizations on which this analysis is based. It is clear that if we had several earths for comparison, such a statement concerning the pattern of welts common to all would indeed have the character of a law. Logically, therefore, apart from the uniqueness of the earth, this statement has its place among the laws.

Law 17 a. The modern crustal folds, on one side of the globe, radiate outward from a focal point in the Hindu Kush and Pamirs. Strong multiple branches extend out toward the west, to the southeast, and to the northeast, and weaker branches run northward across the Eurasian continent and southward into the Indian Sea. On the other side of the globe, the crustal folds encircle the Pacific Ocean. Offshoots exist in both parts.

In addition to this rather lengthy description we must specify the well known asymmetry in the distribution of elevations:

Law 17 b. By far the greatest extent of excessively high land (say, above four thousand meters elevation) is found at the focal point and immediately adjoining it in the east-west trending eastern branch of the Himalayas (and the Tibetan plateau). There is only one other region comparable in widespread great uplift, the central Andes, which trend essentially north-south. These two unique regions lie not far from antipodal to each other.

4. The Compound Belts of post-Algonkian Orogenesis

The compound belts defined. So far we have completely neglected the structural evidence of orogenic movements, the existence of rock-folding. Even where age-long denudation has levelled the crustal folds, the denuded geosynclines exhibit the evidence of former movements, the existence of mobility in the belts of crustal folds. In a later chapter we shall discuss this evidence in detail. At this point we turn our attention to the zones on the earth's surface within which rock-folding has taken place since Cambrian time. The shaded areas in Fig. 23 show the extent of most of these belts in generalized form.

Within these belts geosynclinal sinking followed by folding of sediments virtually came to an end at some places in earlier Paleozoic times, at others late in the Paleozoic, at still others during the Mesozoic or during the Tertiary, while there are places where it is still in progress. Yet orogenic movements have not completely ceased in most of these regions as is shown by the distribution of the modern welts. It is this plain fact that gives us the right to treat such belts as a unit, contrary to current custom. The age relations will form an important part of our discussions later. We shall also have to study carefully the relation of younger to older deformations in the same belt. All we

are here concerned with is this, that in spite of their heterogeneous character these wider zones constitute a large unit. We shall refer to them as the compound belts of post-Algonkian orogenic deformation or, more briefly, the "compound belts."

In a number of places these "compound belts" extend into regions essentially free from modern welts. This is true, for instance, of most of the Appalachian zone northeast of the Hudson River, especially of its continuation on Newfoundland. It is also true of the Hercynian folds of northwestern France and southwestern Great Britain. Another significant case is that of the folded axis of the lowly Timan Range which trending northwestward appears as a weaker branch leading away from the Urals by virgation, and which continues northwestward into the Kanin peninsula.

On the opposite side of the equator, the folds of the Cape Province that seem to be out of place in their isolation lie in the continuation of the belt that otherwise is indicated only by the submarine ridges of the Laccadive and Maldive Islands and the Seychelles arc. They are the only suggestion of former orogenic activity in this zone. As a last significant case of this sort we list the early Paleozoic folds of the Province of Buenos Aires in Argentina south of the Rio de la Plata.[46] These folds strike the coast at right angles with a southeastward trend. Toward the northwest, in line with the strike of these folds, lie the structures of the Sierra de Cordoba and the Argentinian Pre-Cordilleras.

When we now compare Fig. 23 with any good atlas, we see at once that with but few exceptions the modern crustal folds of the continental areas lie inside the compound belts of rock-folding. For the oceanic regions no statement is possible, of course. For the sake of precise argument, we shall restate this observation as a law.

Law 18. The modern crustal folds lie essentially within broader belts, the "compound belts" of post-Cambrian orogenesis.

Truncated ends of compound belts. In a later chapter we shall attempt to analyze the nature of these compound belts. Taking them, for

[46] I. Keidel, "La Geología de las Sierras de la provincia de Buenos Aires y sus relaciones con las montañas de sud África y los Andes," *República Argentina, Anales del Ministerio de Agricultura, Sección geología,* Tomo XI, Núm. 3, Buenos Aires, 1916.

the present, as the complex units they are, we note that in a greatly expanded fashion they display the same pattern which we have defined for the modern crustal folds. In addition, they show very definitely another property. At a number of places the folded belts are truncated by the sea. The Appalachian folds in Newfoundland; the west-east trending ranges of the north shore of Venezuela cut-off on Trinidad; the older Paleozoic folds of the province of Buenos Aires in Argentina; the Paleozoic folds of South Africa; the Alpine system from Cape Ghir in Morocco to the Bay of Biscay; the Paleozoic folds of northwestern Europe, from Brittany to southwestern Ireland; the early Paleozoic folds of Scandinavia north of Varanger Fjord; the folds of the Timan Range west of the mouth of Pechora River. These are the chief examples. The following law expresses the way in which such truncated belts are related.

Law 19. In most cases, where an orogenic belt is cut off by the sea, there exists across the water a corresponding truncated end of another belt which, in some ways, decidedly parallels its counterpart both in the nature of formations and the sequence of diastrophic events recorded in its structure.

Marcel Bertrand[47] was the first to call attention to one of these curious far-flung relationships, that which exists between the geosynclinal belts of northwestern Europe and the Appalachians. Haug emphasized the strong Alpine traits in the stratigraphy of Trinidad[48] which points to the western terminus of the Atlas Mountains. The most surprising of all is the distinct correspondence between the Sierras of Buenos Aires and the folds of the Cape Colony, first observed by Keidel.[49]

[47] Marcel Bertrand, "La chaine des Alpes et la formation du continent Européen," *Bull. Soc. Géol. France*, 3e sér., Vol. 15, 1886-1887, p. 442. See also E. Suess, "Ueber die Asymmetrie der nördlichen Halbkugel," *Sitz. Ber. Kgl. Akad. Wiss., Wien, Math.-nat. Kl.*, CVII, Abt. 1, 1898, pp. 89-102; E. Suess-DeMargerie, *La Face de la Terre*, Vol. III, Part 2, 1918, pp. 595-662.

[48] Emile Haug, "Les géosynclinaux et les aires continentales, contribution à l'étude des transgressions et des régressions marines," *Bull. Soc. Géol. France*, 3e sér., Vol. 28, 1900, p. 636.

[49] J. Keidel, "La geología de las Sierras de la provincia de Buenos Aires y sus relaciones con las montañas de sud África y los Andes," *Republica Argentina, Anales del Ministerio de Agricultura, Sección geología*, Tomo XI, Núm. 3, Buenos Aires, 1916.

The distance between the corresponding ends is fully four thousand miles. Compared with these extreme cases, the others appear almost obvious. Thus parallels exist between the Timan Range and the folds north of Varanger Fjord.[50] The Caledonian folds of Scandinavia may be continued in Spitzbergen beneath the Devonian unconformity.[51] If so, these Caledonian folds may be connected with the folds of the United States Range, in northernmost Greenland and Grant Land.[52] The Ural Mountains find their continuation in Novaya Zemlya. An eastern offshoot is cut off by the Kara Sea. It is to be expected, by analogy with the other examples, that these loose ends bear relations to the folds of Taimyr Peninsula and the similarly unexplored Verkhoyansk Mountains.

A test case for Wegener's interpretation. There can be little doubt concerning the reality of these relations. But what do they mean? Wegener points to the three transatlantic correlations as exquisite evidence of continental drifting. The belts correspond because they were originally in contact and have been pulled apart. The distance from Newfoundland to the province of Buenos Aires is, in fact, comparable to that between southern Ireland and the Cape Colony. It is true, on the other hand, that the fit of the coast lines between these two points is bad as anyone can find out with the aid of a globe and tracing paper.[53] Yet, we have seen already that "mobilism" grants continents that are capable of drifting also the capacity for stretching and deforming to suit its needs. Indeed, if Argand's view of the relatively high plasticity of continental floes is accepted, then it is rather surprising that the outlines have retained any degree of similarity.

Let us examine one example in greater detail. We choose the most impressive of all, the correspondence that exists in stratigraphy and

[50] E. Suess-DeMargerie, *La Face de la Terre,* Vol. III, Part 2, p. 534.

[51] *ibid.,* Vol. II, p. 100.

[52] Lauge Koch, "Preliminary Report upon the Geology of Peary Land, Arctic Greenland," *Am. Jour. Sci.,* 5th ser., Vol. 5, 1923, map, Fig. 1, p. 190. On this map the folded system of the United States Mountains is labelled "Caledonian Folding." There are indications of later compressive movements, but the main period of folding seems to be of Caledonian age.

[53] See, e.g., Charles Schuchert, "The Hypothesis of Continental Displacement," in the symposium on *The Theory of Continental Drift,* published by the American Association of Petroleum Geologists, 1928.

structure between the folded belt in the south of the Cape Colony and the Sierras south of Buenos Aires in the Argentine.[54] The similarities may be summarized as follows:

In both regions:

1. A pre-Devonian rock series rests with strong angular unconformity on pre-Cambrian crystallines.
2. The first richly fossiliferous formation (Lower Devonian) is underlaid by a thick series of white fine-grained quartzites. They appear intensely folded in both regions, the thin beds showing abundant minor drag folds.[55] The similarity in the lithology and the pattern of folding is striking in the two remote regions.[56]
3. The Lower Devonian series consists of clastic rocks (shales and sandstones) and contain a rich marine fauna. Numerous species of the Bokkeveld fauna of the Cape Mountains occur in the corresponding Lower Devonian beds of the Argentine Sierras.
4. A great stratigraphic break marks the appearance of the Permian terrestrial beds.
5. The basal beds are tillites interbedded with marine strata (known as the Dwyka conglomerate in South Africa). At least one Per-

[54] Alex. L. Du Toit, "A Geological Comparison of South America with South Africa," *Carnegie Inst., Pub. 381*, 1927. Also discussions at various places in Alex. L. Du Toit, *The Geology of South Africa*, Edinburgh (Oliver and Boyd), 1926 (a classical summary of regional geology); J. Keidel, "La geología de las Sierras de la Provincia de Buenos Aires y sus relaciones con las montañas de Sud África y los Andes," *Republica Argentina, Anales del Ministerio de Agricultura de la Nación, Sección geología*, Tomo XI, Núm. 3, 1916. (Also a briefer account, "Ueber das Alter, die Verbreitung und die gegenseitigen Beziehungen der verschiedenen tektonischen Structuren in den argentinischen Gebirgen," *Congr. géol. internat., XII, 1913, Compt. Rend.*, pp. 671-87.) A valuable summary of the points of comparison between the two regions is contained in Charles Schuchert, "The Hypothesis of Continental Displacement," in *The Theory of Continental Drift*, a symposium published by the American Association of Petroleum Geologists, 1928, pp. 104-44.

[55] The stratigraphic relations to the Lower Devonian shales is not easily determined in the Argentinian Sierras, where they crop out chiefly in the Sierra de la Ventana (Keidel, *op. cit.*, 1916, pp. 21-2). But the position below the Lower Devonian shales, that is, stratigraphically equivalent to the quartzites of the Table Mountain Series of South Africa, seems now established.

[56] Compare Pl. VI of Keidel's paper of 1916 and Pl. XIV, opp. p. 174, of Du Toit, *The Geology of South Africa*, 1926.

mian reptile genus, *Mesosaurus*, is common to southern Brazil and South Africa.

6. The higher Permian beds of southern Brazil carry the *Glossopteris* flora which is characteristically associated throughout the southern hemisphere with the presence of basal tillite beds.
7. The overlying Triassic is represented in a large part by red beds. In these a parasuchian reptile genus, *Erythrosuchus*, is found in South Africa which is closely allied to a Brazilian form, *Scaphonyx*.[57]
8. In latest Triassic time, basic lavas were poured out. In South Africa, they form the stratified dark lava series with interspersed sediments which forms the bold escarpment of the Drakensberg, after which it is named. They were followed by large intrusions of dolerites throughout the Karroo basin, Orange Free State, and Natal, in the form of sills and vertical dikes (probably of early Jurassic age, certainly pre-Cretaceous). Similarly, extrusive basalts and intrusive "dolerites" occupy the basin of the Parana and Uruguay Rivers.[58]

This similarity in the geology and paleontology of two regions separated by a distance of four thousand miles is indeed remarkable. It extends northward into southern Brazil and in the south to the Falkland Islands. Du Toit summarizes his impression of these relationships as follows:

"So extraordinary indeed are the resemblances—amounting almost to identity—of the Devono-Carboniferous successions in the Falkland Islands, Argentina, and southern Brazil, that a comparison therewith cannot be omitted.

"Although the South Atlantic intervenes, the description just given of the Cape system applies almost word for word to the beds in the Falklands, the three divisions in those islands being all but identical in their lithology, thickness (so far as can be judged), and fossils with those of the Cape, and are overlain by the Lafonian tillite, the undoubted equivalent of the Dwyka conglomerate.

[57] Du Toit, *op. cit.*, p. 270.

[58] C. L. Baker, "The Lava Field of the Parana Basin, South America," *Jour. Geol.*, Vol. 31, 1923, pp. 66-79 (with a sketch map, Fig. 1, p. 70).

"In Argentina the Sierra de la Ventana north of Bahia Blanca displays an isoclinally folded and inverted succession closely paralleling that between Oudtshoorn and Prince Albert; from the ancient granite through the lower thick mass of fine-grained quartzites, through soft slates and fine grained greywackés, with occasional Devonian fossils, coarse unfossiliferous greywackés representing the Witteberg Beds, and an apparently conformable thick tillite and strata presumably of Karroo age. . . .

"This wonderful lithological, paleontological, and structural parallelism between South Africa and South America during this epoch cannot be sufficiently emphasized. Taken in conjunction with the evidence of a similar kind during the Permian and Triassic, it proves the intimate connection of these two continents over an enormous period of time."

The last sentence of the quotation from Du Toit's book reflects the trend lines of Wegener's reasoning. Before we can accept the evidence of this remarkable parallel of events as proof of such reasoning, we must ask two questions: First, is the assumption of an original actual contact of the two continents or at least a close proximity sufficient to account for all essential lithologic and structural features of the two regions? And further, is it necessary for a satisfactory explanation of the similarities?

Taking up the first question, we find several discrepancies in the times of orogenic movements in the two regions which if reliable would preclude such close proximity as the hypothesis demands. But the geological mapping and structural analysis of the Argentine Sierras is as yet in a reconnaissance stage and it would perhaps be unfair to press this point.

There is, however, one feature which can hardly be dismissed so briefly. The Karroo system of South Africa, which comprises at least two periods, the Permian and the Triassic, has furnished a large number of species of reptiles. The richest reptile beds, in the Upper Permian alone have furnished something like seventy species.[59] It is indeed remarkable that such a host of unusual forms should have escaped the notice of collectors in the Argentine and southern Brazil to this day. It seems more probable that they are not present in the South American fauna. That, however, would be entirely unintelli-

[59] Ch. Schuchert, *op. cit.*, p. 123.

gible if the two continents had been in contact. The Dinosaurs of the Upper Triassic (Stormberg) red beds are fewer, but even more significant for two reasons. The larger dimensions of their bones render them more conspicuous and, in contrast to the Permian forms, they are known from widely separated parts of the world. *Thecodontosaurus*, for instance, is also known in fragments from England, Germany, eastern United States, east India, and Australia. *Plateosaurus*, an animal of a total length of about twenty feet, is known from France and Germany as well as from South Africa.[60]

Such a discrepancy in faunal content is indeed difficult to understand if the two regions once had been joined. Yet in a generous mood we might be willing to consider such negative evidence as insufficient to outweigh the undoubtedly remarkable similarities in lithology and structure of the two regions. We might be inclined to consider the Wegener hypothesis as sufficient to explain the positive evidence. There still remains the more important question: Is the hypothesis necessary?

The resemblances listed above concern (a) a far-reaching similarity in orogenic and volcanic history expressed in the sedimentary record and in the structure; (b) one marine fauna (Lower Devonian) with numerous species in common in both regions; (c) a few terrestrial reptiles in common in the Permian and Triassic.

Not one of these resemblances is peculiar to regions suspected of having once been in contact. For an example we turn to two regions also roughly four thousand miles apart, the eastern Alps and the central Himalayas. The Mesozoic faunas of the two regions show far-reaching similarities. This is true especially of those of the Triassic. In his *Geology of India for Students* (1926), Wadia says: "The faunistic resemblance between the Triassic rocks of the Himalayas and Alps suggests open sea communication maintained by the Tethys between these two areas since the beginning of the Permian. This sea provided a free channel of migration and intercommunication between the marine inhabitants of the central zone of the earth from the Mediterranean shores of France to the eastern borders of China, and maintained this waterway up to the beginning of the Eocene period." The Upper Triassic (Upper Carnic and Noric) beds espe-

[60] Karl A. von Zittel, *Grundzüge d. Palaeontologie*, II Abt., "*Vertebrata*," 2nd ed., München u. Berlin, 1911, pp. 279-80.

cially such as the *Tropites subbullatus* beds and the *Halorites* beds carry a fauna astonishingly like that of the corresponding limestones of Hallstadt in the Eastern Alps. Perhaps the four thousand miles between two regions in an acknowledged Mediterranean zone, such as that of the Tethys, seem less significant than the same distance measured across an ocean. Then go east from the central Himalayas half around the circumference of the globe, across the Pacific, and find the same *Tropites subbullatus* fauna of the Carnic series in California.[61]

Such an appearance of faunas having many species in common[62] in regions separated by enormous distances is indeed a well known fact. We are deceiving ourselves if we mistake the similarities of the South African and South American Lower Devonian faunas for something unique.

But there remains the remarkable similarity in the lithological character of significant stratigraphic units. In this respect also a comparison of the Eastern Alps with the Himalayas is illuminating. In the Austrian Alps the uppermost Triassic (Rhaetian) sediments are represented by massive, thick limestones ("Dachsteinkalke") with thick-shelled, large pelecypods of the genus *Megalodon*. Entirely comparable massive limestones crown the Upper Triassic series of the Himalayas, equally characterized by *Megalodonts*. This is as conspicuous a lithological parallel as one could wish between regions four thousand miles apart.[63]

Both lithologic and structural resemblances between the Eastern Alps and the Himalayan belt become most pronounced toward the end of the Mesozoic and in the Cenozoic. In the Himalayas, the end of the Mesozoic is marked by the formation of a great thickness of unfossiliferous shales and more or less shaly sandstones. These correspond in every respect to the Flysch series of the Alps and of all

61 J. P. Smith, "Periodic Migrations between the Asiatic and the American Coasts of the Pacific Ocean," *Am. Jour. Sci.*, 4th ser., Vol. 17, 1904, p. 219.

62 Modern refinement in taxonomic observation tends to emphasize minor constant differences between closely allied species in different regions by the giving of distinct species names. The result is that lists of names alone more and more fail to indicate regional relations that are most significant. This is a loss out of proportion to the accuracy gained. A triple nomenclature would be less misleading.

63 This is the more remarkable since Rhaetian Megalodon limestones seem to be unknown in the long interval between the Eastern Alps and the Hindu Kush. (See E. Suess-DeMargerie, *La Face de la Terre*, Vol. II, p. 444.)

the folded mountain chains between the Alps and the mountains of Burma. The "Flysch" of the Burmese chains duplicates that of the Carpathians and of the Caucasus to such details as included serpentines, the presence of petroleum, of salt springs and mud volcanoes.[64] Exactly as in the Alps, the Flysch facies extends into the Eocene and here bears nummulite beds, partly in the form of nummulite limestones. As in the Alps, the marine Eocene formations assume the character of nummulite limestones away from the axes of the rising mountain chains, as in the fossiliferous nummulitic limestones of the hill ranges on the boundary between Sind and Baluchistan.

As in the Alps, a sharp tectonic line separates the inner belt of intensely folded Cretaceous and Eocene rocks from the outer zone of younger Tertiary formations. These are in both regions terrestrial, largely detrital rocks, known as the "Molasse" facies in the Alps. The thick and coarse conglomerates of the Alpine Molasse form separate distinct fans, as detailed mapping has shown.[65] In the Western Alps the grouping is such that it has suggested a relation to the mouths of existing transverse valleys. We are here not concerned with the validity of such a relation. It is noteworthy, however, that exactly similar relations have been inferred for the conglomerates in terrestrial formations of later Tertiary age at the foot of the Himalayas.[66]

Locally, on the north side of the Alps, fossiliferous marine beds are intercalated between the Neogene terrestrial formations. They mark a minor transgression in Burdigalian time. In the Tertiary section, which because of its exceptional development serves as the type section for the Tertiary of the whole of India, in the hill ranges of Sind in front of the Alpine mountains of Baluchistan, marine beds are intercalated between a lower and an upper terrestrial "Molasse" series. This fossiliferous upper Gaj series is the exact equivalent of the marine Molasse of the Alps and like it is of Burdigalian age.[67]

In contrast to the inner Flysch zone, the Molasse belt is thrown into broadly anticlinal structure. It dips under toward the mountains and is overthrust by them, in India exactly as in the Alps.

[64] E. Suess-DeMargerie, *La Face de la Terre*, Vol. I, p. 596.
[65] See, e.g., Pl. IV, opp. p. 48, in Alb. Heim, *Geologie der Schweiz*, 1919, Vol. I.
[66] E. Suess, *The Face of the Earth* (trans. by Sollas and Sollas), Vol. I. p. 432.
[67] D. N. Wadia, *Geology of India*, 1926, p. 210.

This may suffice to show that resemblances in structure, orogenic history and lithologic units, at least as remarkable as those existing between the Argentine and South Africa, are found in regions similar distances apart which certainly never were in close contact. Such resemblances testify to a common dynamic history of points along extended orogenic belts, but in no way demand the bodily contact which Wegener's reasoning implies.

Similarly, the eruption of plateau basalts points to analogous stress relations, not necessarily to areal unity of distant regions.

The famous realm of the Tertiary plateau basalts from Greenland to southern Siberia may serve to illustrate this point. For the part lying west and north of Novaya Zemlya, Washington has proposed the name "Thulean Basalts."[68] Harker thinks that ". . . for any evidence to the contrary, a continuous lava field may have stretched from Antrim to beyond Franz Josef Land, a distance of two thousand miles."[69]

From Franz Josef Land it is but a short distance to the mouth of the Yenisei where the first outliers of the Siberian basalts lie, which extend southeast another fifteen hundred miles[70] and more.

The whole problem of plateau basalts is tied up with specific stress relations which have recurred independently at different times in most parts of the earth. That outside a belt of common orogenic history there should be plateau regions of comparable dynamic history is not surprising. But such a common history certainly cannot be adduced as evidence of a former geographical proximity.

Of the lines of resemblance which we listed at the beginning of this critical discussion, there remains one. The two regions, four thousand miles apart with one ocean between them, have twice shared at least one genus of terrestrial reptiles, in Permian time and again in Triassic time. In view of the numerous other South African reptiles which fail to appear in South America, somehow this point lacks force. And yet, it is curious that continents separated by four thousand miles of sea and (at present) not connected by any land bridge

[68] H. S. Washington, "Deccan Traps and Other Plateau Basalts," *Bull. Geol. Soc. America,* Vol. 33, 1922, p. 780.

[69] A. Harker, "Some Aspects of Igneous Action in Britain," *Quart. Jour. Geol. Soc.,* Vol. 73, 1918, p. xcii.

[70] See, e.g., H. S. Washington, *op. cit.,* 1922, p. 791; F. von Wolff, *Der Vulkanismus,* Band I, pp. 152-3.

however slender, should have in common any higher terrestrial forms. On second thought, however, we realize that such instances of common organic forms do not prove the point.

In our day, the genus *Alligator,* so characteristic of southeastern North America, is found in the Yang-tse region of China[71] (*Alligator sinensis Faew.*). This is surprising, especially since the alligator is completely absent from the whole west and northwest of our continent and from western Asia and Europe. There are other reptile forms common to the two regions which lie on opposite sides of the globe. Of the lizards (skinks) the genus *Eumeces,* characteristic of the eastern United States, is found in China in three species. Of the genus *Lygosoma* one species even is said to be common to the Yang-tse region and the eastern United States (*Lygosoma laterale Lay*). The only poisonous snake of northern and central China is closely related to our rattlesnake. Among the amphibians, the giant salamanders (*Amphiumidae*) are limited to the eastern United States and to the systems of the Yang-tse and Hoang-ho Rivers in China. Of the ganoid fishes, the toothed sturgeons (*Polyodontidae*) are limited to the same two regions.[72]

A comparison of the flora of the eastern United States with that of eastern China and Japan yields even more striking results. In a paper published in 1872, Asa Gray[73] listed 241 species of Atlantic North America which have close representatives in eastern Asia. Two-thirds of these are unrepresented in California. Subsequent work has unquestionably altered these figures, but cannot have changed the ratios materially. The list comprises many well known forms such as Magnolia; Wisteria; Cladrastis (Yellow Wood); Rhus vernix (Poison Sumach); Liquidambar (Sweet Gum); Liriodendron (Tulip Tree); Sassafras; Panax (Ginseng); Hydrangea, etc. Speaking of four genera of the family Berberidaceae (Podophyllum—our May Apple; Jeffersonia—twin leaf; Caulophyllum; and Diphylleia),

[71] See "Atlas of Zoogeography," *Bartholomew's Physical Atlas,* Vol. V, Edinburgh, 1911, Pl. xx, map iv.

[72] These illustrations are quoted from W. Kobelt, *Die Verbreitung der Tierwelt, gemässigte Zone,* Leipzig, 1902, p. 257. For the *Amphiumidae* see "Atlas of Zoogeography" quoted above, Pl. xxi, map vi; for the *Polyodontidae, ibid.,* Pl. xxv, map vi.

[73] Asa Gray, *Proc. Am. Assoc. Adv. Sci.,* Vol. 21, 1872, pp. 1-31. The writer is indebted to Professor Robert Griggs for reference to this paper and for assurance that it is essentially still valid.

Gray wrote: "Here are four most peculiar genera of one family, each of a single species in the Atlantic United States, which are duplicated on the other side of the world either in identical or almost identical species or in analogous species, while nothing else of the kind is known in any other part of the world."

This illustration deserves the space we have devoted to it. It should make clear the danger of basing an argument on isolated examples chosen for the purpose from a vast and complicated field with which the geologist is not acquainted. Isolated facts may well be grouped impressively. We must not allow them to bear weight so long as they remain separated from the body of knowledge to which they belong, which as a whole must be elucidated by the theoretical picture we aim to develop.

This discussion shows the basis of the writer's conviction. It is at best doubtful whether the assumption of a former contact of South America with South Africa would prove sufficient to account for the ensemble of geological and paleontological realities in the two continents;[74] it is certain, that such an assumption is not necessary to explain any and all of the observed resemblances.

The interpretation here adopted. The observed correspondences, however, seem to point inevitably to some sort of connection between opposed truncated ends of mobile belts. This connection does not necessarily have to be topographic. On winter mornings on a frozen pond one may see cracks along which water has risen and frozen when reaching the surface, forming welts that rise conspicuously above the smooth surface of the ice. The writer has seen such cracks repeatedly which for distances of dozens of yards showed no trace of such welts and were recognizable only by the total reflection of light in the ice while beyond such stretches they were marked again by prominent welts. This may serve as one example of disconnected welts which are dynamically a unit. In Quirke's experiments,[75] welts arose that were disconnected and yet were formed simultaneously under a common set of crustal stresses. Other cases could be thought out. It is sufficient here that we realize that dynamic connection does not necessarily mean topographic connection.

[74] For other significant discrepancies see, e.g., H. S. Washington, "Comagmatic Regions and the Wegener Hypothesis," *Jour. Washington Acad. Sci.*, Vol. 13, 1923, pp. 343-6. Also E. Krenkel, *Geologie Afrikas*, Vol. I, 1925.

[75] See p. 116, Fig. 25.

Actual connecting crustal folds may, however, exist beneath the cover of the ocean. We shall do well to remember that compared with the hypsometrical maps of the continents even the most authentic bathymetrical charts of the oceans are based on most inadequate data. For depths of more than 3,000 feet soundings spaced as closely as one sounding per 500 square miles are rare.[76] J. Thoulet has published an interesting set of maps[77] to show to what extent even the major features of topography are lost on contour maps through such inadequate spacing of elevations. These maps show the topography of France, represented by contours drawn for elevations approximately 1 per 10,000, 5,000, 1,000, 500 square miles, respectively. They are illuminating indeed and well worth consulting. In the most favorable case, even the broadest aspects of the topography of the country, as we know them, are barely recognizable. For a large part of the ocean floor, however, in the Atlantic Ocean especially in its southern part, the density of soundings is less than in the worst of the illustrations given by Thoulet. We must not be surprised, then, if our maps of the ocean floor are disturbingly different from what we have reason to expect.

The most authentic map of the Atlantic Ocean known to the writer is that published in 1912 by Max Groll.[78] The contours used on this map are —200 meters, —1,000 meters, —2,000 meters, etc., down to less than —8,000 meters. Let us see how much of our southern Appalachians would appear on a map drawn with such contour intervals. Suppose the southern Appalachians submerged under a water surface standing at an elevation of 7,000 feet above present sea level. Soundings from this hypothetical sea level downwards at —200 meters, —1,000 meters, and —2,000 meters would correspond to the actual contour lines of our maps of 6,350 feet, 3,700 feet, 400 feet. Fig. 24 shows the corresponding map. This map is, however, based on complete surface data. The critical areas are so small that it is

[76] Max Groll, "Die Lotungsdichtekarten von J. Thoulet," *Petermanns Mitt.*, Vol. 59, 1913, 1. Halbband, p. 251.

[77] J. Thoulet, "Densité de sondages et veracité des cartes bathymetriques sous-marines," *Ann. de l'Inst. Océanogr.*, Paris, 1911. The maps are reproduced (in colors) in *Petermanns Mitt.*, Vol. 59, 1913, 1. Halbband, opp. p. 280, accompanying Max Groll's review quoted above.

[78] Max Groll, "Tiefenkarten der Ozeane," *Veröff. Instit. f. Meereskunde d. Univ. Berlin*, N. F., A, Geogr.-naturh. Reihe, H. 2. Three maps, showing the Atlantic, the Indian, the Pacific Ocean, each on the scale 1:40,000,000.

obvious that the chance of striking them blindly with a plumb line at stations scattered on the average one to, say, one thousand square miles is small indeed. In other words, it is likely the whole range would fail to appear on our map.

The introduction of the sonic depth finder promises to remove this obstacle to understanding in the near future. We can estimate the meaning of this change if we take, for instance, the best bathymetric map of the shelf off southern California based on data obtained with the plumb line alone and compare it with the new map constructed from many more observations with the sonic depth finder.[79] The *Meteor* recently returned from an extensive cruise bringing back 70,000 determinations of depth on the mid-Atlantic ridge. Progress should be rapid. But we will do well to await the accumulation of data instead of losing ourselves in speculations.[80]

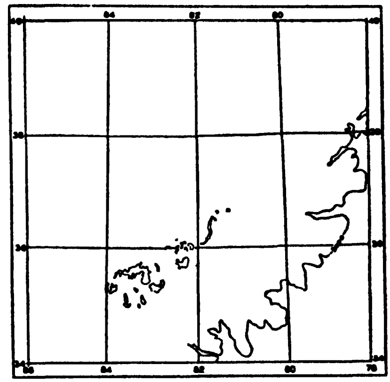


Fig. 24. Contour map of 60 square degrees in the southeastern United States, with the southern Appalachians in the center. (Long. 76°-86° W.; lat. 34°-40° N.)

Intended for comparison with the submarine topography as shown on Max Groll's maps of the oceans. The contours shown are 450 feet, 3,750 feet, 6,400 feet A.T. which correspond to the intervals used by Max Groll, when sea level is imagined at 7,000 feet above its present position (—200 meters, —1,000 meters, —2,000 meters).

We are now ready to summarize the outcome of this discussion in the form of a definite opinion.

Opinion 12. The orogenic belts of the continents do not constitute the whole of the pattern of the earth's zones of mobility. There must be included in it lines that connect the truncated ends of these zones across the Atlantic (and perhaps also the Indian Ocean). These con-

[79] Chart issued by the Hydrographic Office of the U.S. Navy, showing the configuration of the continental shelf off the coast of California out to the 2,000-fathom contour. Based on about 5,000 new soundings made by the U.S. Destroyers *Corry* and *Hull* in 1922.

[80] An interesting, highly speculative attempt to trace the Alpine system of crustal folds across the Atlantic into the West Indies is contained in R. Staub's recent book, *Der Bewegungs-Mechanismus der Erde*, Berlin, 1928, pp. 127-32 and map.

necting lines may or may not correspond to zones of actual crustal folding hidden beneath the oceans.

A word remains to be said about the phrase in parenthesis. In the sense of the foregoing opinion, the West Indies mark the syntaxis of the Cordilleras of North and South America with the hypothetical westward prolongation of the Alpine system.[81] This is the Mesozoic-Cenozoic parallel of the line that connects the Paleozoic Appalachians with the Hercynian system of Europe. It does not seem unreasonable to suspect a similar relation in the South Atlantic. Here the south tip of Patagonia and the north tip of Graham Land both swerve eastward and beyond them lie groups of islands suggesting a hairpin curve, not unlike that of the Lesser Antilles. To the north of this bend lies the hypothetical line that connects the Sierras of Buenos Aires with the folds of the Cape Colony. If we compare this older line with that which prolongs the Appalachians eastward, the eastward swerve of Patagonia and Graham Land correspondingly suggests a parallel with the West Indies. In that case this zone, too, would mark a place of syntaxis, the converging of the crustal folds of South America and of Antarctica with a hypothetical line running westward from a point south of Cape Agulhas. Such a hypothetical line might be considered a prolongation of the submerged ranges of the Indian Ocean.

Here we have gone far into pure speculation. Our argument will not hinge in any way on such speculative connections. We shall let it stand for what it may ultimately prove to be worth.

Looking back over our findings expressed in laws 17 and 19 and opinion 12, we are driven to a conclusion of great importance:

Opinion 13. Taken in their entirety, the orogenic belts are the result of earth-wide stresses that have acted on the crust as a whole.

Certainly the pattern of these belts is not what one would expect from wholly independent, purely local changes in the crust.

We have now arrived at the point where we may ask ourselves if the observed pattern is in any way diagnostic of a specific mechanism.

[81] This interpretation of the Trinidad-Atlas line has been developed recently by Staub (*op. cit.*). The writer advocated the same view in his lecture before the Geological Society in 1920.

5. The Mechanical Interpretation of the Pattern of Crustal Folds

Folds produced in a plastic, weak shell surrounding a contracting core. As early as the sixteenth century, Giordano Bruno compared the wrinkles of a drying apple with the mountains of the earth. Near the middle of the last century, Dana and Le Conte extended this analogy to the mechanism involved. Daubrée seems to have been the first to observe the wrinkling of rubber balloons coated with paint, wax, gum arabic, and gelatin.[82] Similar experiments have since been made repeatedly. Good photographs of such experiments with rubber balloons were published by Toula[83] in 1914. A glance shows that the pattern produced under the conditions of such experiments is radically different from that of the mobile belts of the earth. It consists of a large number of wrinkles of similar dimensions irregularly intertwined and distributed at random over all parts of the surface.

Toula also made experiments in which part of the coating was less flexible than the rest. But his results throughout involve surface tension as one of the factors and are, therefore, not applicable to the earth's crust.

Significant experiments were made by Quirke.[84] He used rubber balls inflated with air and covered with a mixture of paraffin and vaseline. These balls he placed under hydraulic pressure in a specially constructed tank and let the air escape from them slowly.

Two types of deformation were observed. In some cases a single welt formed following a great circle about the sphere. In another experiment, however, two welts formed along great circles, one almost at right angles to the other. Each of these was discontinuous, as shown in Fig. 25.[85] "Where the circles crossed one another there were notable nodal elevations, one on either side of the sphere, almost antipodal one to the other."

Here we see some of the critical features of the modern welt pattern reproduced in principle: The highest modern welts lie roughly

[82] *Bull. Soc. Géol. France,* 3e sér., Vol. 7, 1879, p. 152. Quoted from A. Daubrée, *Études synthétiques de géologie expérimentale,* Paris, 1879.

[83] F. Toula, "Schrumpfungsversuche," *Petermanns Mitt.,* Vol. 2, 1914, pp. 8-15 (with illustrations on six plates).

[84] T. T. Quirke, "Earth Deformation," *Congr. géol. internat., XIV, 1926, Compt. Rend., Fasc. 4,* 1928, pp. 1537-53.

[85] Reproduced from *op. cit.,* Fig. 3, p. 1541. The crack shown in this picture is almost certainly the result of expansion due to the removal from the pressure tank.

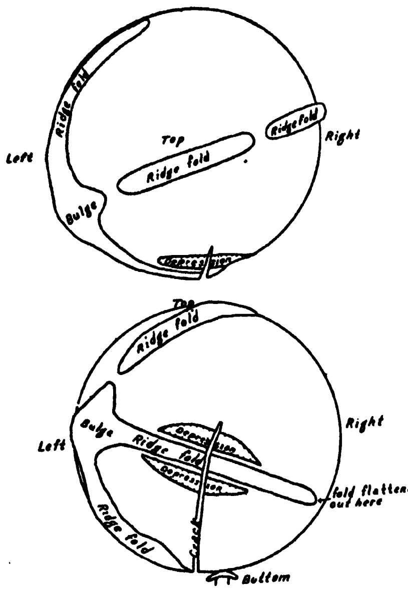


Fig. 25. Pattern of welts produced under hydraulic pressure on a shrinking rubber ball coated with a mixture of paraffin and vaseline. Top and side views.
(Quirke, 1926)

in two circles more or less at right angles to each other (the circum-Pacific and the Mediterranean-Himalayan belts); the belts are discontinuous and yet dynamically part of a common plan; near the point of junction of the two circles "nodes" of exceptional elevations exist lying approximately antipodal to each other.[86]

The fact that these features were all produced simultaneously, in one experiment, justifies the belief that the process of welt formation was actually reproduced in principle. In contrast to Quirke's analysis, however, the writer believes that the weak, plastic behavior of the crust is the fundamental factor in the experiment.

While Quirke's experiment thus reproduces most of the essential features of the present-day welts, it does not reproduce all. In the experiment, the two "nodal" points are equally developed. On the earth, however, the mountain knot of central Asia is unique with its multiple branches radiating from it. Nor is there any indication of the characteristic details of the patterns of modern welts. Apparently, another factor enters which is not covered by Quirke's experiments. We will do well, therefore, to examine the results of other experiments.

Fractures produced by compression of a relatively strong, brittle shell. The writer produced tangential deformations in more or less brittle shells by placing them under hydrostatic pressure in a simple

[86] The presence of two depressions along one of the welts may not be as significant as it may seem at first. The difficulty of applying a uniform coating must be considered. No such depressions were observed in the other experiments.

apparatus constructed by the writer's colleague, Dr. R. C. Gowdy.[87] Pressures over 200 pounds per square inch were obtainable, but none of the spheres used required over 100 pounds to produce failure, some breaking at pressures of 25 and 30 pounds.

Two kinds of spheres were used in these experiments, paraffin-coated rubber sponge balls and the thin glass spheres used as ornaments on Christmas trees. The smooth surface of the commercial rubber balls was removed with sandpaper, exposing the vesicular texture of the spongy interior. The rough surface caused the paraffin coating to be interlocked with the body of the ball. To prevent a complete shattering of the glass spheres, some were covered with a thin coat of collodion and others were filled with a solution of gelatin beaten to a foam. The best results were obtained through a device introduced by Dr. Gowdy. A thick-walled bulb with a fine capillary stem was attached to the neck of the glass sphere by means of a short section of rubber tubing.[88] The capillary tube allowed a gradual adjustment of pressure and failure consequently occurred without great violence.

The results in all cases were essentially the same. This is most important, since the degree of brittleness varied between the extreme of glass on the one hand and a coating of paraffin in warm water on the other. At the same time the thickness varied from the very thin glass balls to relatively thick coatings on the rubber balls. Thus thickness and physical properties varied between limits wide enough to eliminate accidental effects and bring out the general pattern of fracture of any relatively strong shell under uniform tangential pressure.

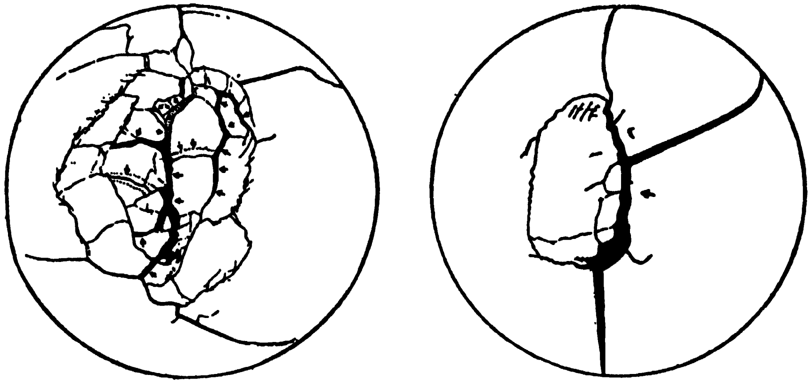
The resulting pattern is most clearly shown in the fractured paraffin shells. Figs. 26 and 27 may serve as illustrations.[89] Fig. 27 shows the simplest case. An oval fragment has been broken from the sphere. On the east side this fragment is bounded by a strongly oblique fracture, dipping eastward, marked in the figure by hachures. The arrow indicates the direction in which the eastern hanging wall of the fracture overrode the footwall as was clearly shown by the striations on the slickensided fracture surface. The overriding caused a bending of the

[87] Walter H. Bucher, "The Pattern of the Earth's Mobile Belts," *Jour. Geol.*, Vol. 32, 1924, pp. 265-90. The reader is referred to this paper for a description of the apparatus.

[88] See illustration in Walter H. Bucher, *op. cit.*

[89] Walter H. Bucher, *op. cit.*, Figs. 15 and 14, p. 287.

area to the west of the fracture. This broke along a curved line made up in a zigzag fashion of alternating short stretches of conjugate



Figs. 26 and *27.* Thin spherical shells of paraffin fractured under hydraulic compression. The shells were immersed in warm water to reduce the brittleness of the paraffin.

The arrows indicate the directions in which overthrusting took place along the inclined (hachured) thrust planes. Note the zigzag pattern and the associated conjugate joints of the boundary fractures. The gaping fractures (thick black lines) have resulted from expansion after the pressure was released.

(W. H. Bucher, 1924)

joint systems such as are the inevitable result of the simultaneous action of tensional and compressional stresses.[90] With the detachment of the oval area the tangential stresses were relieved in all directions and nothing more happened. The width of the gap left when the sphere returned to its original shape upon removal of pressure gives a direct measure of the amount of compression. The three cracks that run north, northeast, and south show vertical and unstriated walls and can therefore not possibly have formed under compression. They are clearly tension cracks that originated when the pressure was released and the interior rebounded into its original shape.

Fig. 26 shows the same type of deformation. Here roughly semicircular fragments were detached from the spherical shell on both sides of the original fracture, as a result of the downward bending of the surface on one side and the upward bending on the other. The conjugate joint systems which together make up the zigzag margins

[90] Walter H. Bucher, "The Mechanical Interpretation of Joints," *Jour. Geol.,* Vol. 28, 1920, pp. 707-30; Vol. 29, 1921, pp. 1-28.

of the east and west sides of the detached area are beautifully developed. Again the fractures that radiate from this central area of compression are pure tension cracks formed after the pressure was released and have nothing to do with the deformation under compression.

Experiments with glass spheres showed the same detachment of a more or less oblong area and radiating from this area tension cracks with normal walls.[91]

We may summarize the result of these experiments as follows: Pressure exerted on the outside of thin-walled shells causes a single compact area to be detached from the shell. This area is bounded on the outside by fractures produced under torsional strain and is traversed on the inside by one or several inclined thrust planes which mark the original places of failure. This obviously means that once the tangential pressures have been relieved within a small area either by the fractures bounding an area or by fractures radiating from one point, all further stresses are transmitted to this point and there relieved.[92]

We may, therefore, state confidently that the pattern of fractures produced by uniform tangential pressure in a thin, relatively strong and brittle shell is fundamentally different from that of the earth's mobile belts.

Fractures produced by tension in a thin brittle shell. A very different result was obtained when spherical shells were subjected to uniform tension. The experiments were made in the simplest manner possible by merely allowing water to freeze in suitable hollow spherical shells.

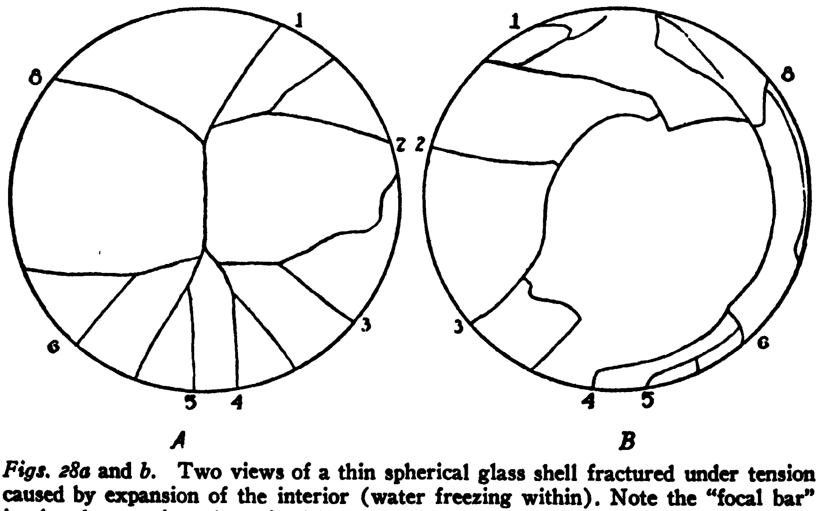
To secure the same range in brittleness and thickness of the shell which was deemed so important in the experiments described above, glass spheres and paraffin spheres were again employed. The glass spheres were the ordinary commercial Christmas tree ornaments. The paraffin spheres were made by the writer by pouring hot paraffin into the glass spheres and turning them rapidly in all directions while

[91] For illustrations see Walter H. Bucher, *op. cit.*, Figs. 12 and 13, p. 287.

[92] It must be remembered that this discussion has a meaning only if the physical condition of the crust is such that stresses may be transmitted. If stresses cannot be transmitted, no essentially simple pattern of lines of yielding can be expected such as we actually see on the earth. It is from the existence of this pattern that we infer that the crust is strong enough to transmit stresses below a certain limiting value.

chilling them. The thin glass form was then removed by breaking it. Such paraffin spheres could be made of fairly uniform thickness with the exception of the point under the neck-shaped opening. Here a coarse vesicular structure always developed producing a corresponding thickening. Yet the variation of thickness in these crudely made paraffin spheres was much greater than in the glass spheres. This caused the pattern of fractures developed in the paraffin spheres to be more irregular and erratic than in the glass spheres. The fact that the general character of the fractures remained the same and was recognizable in all cases, shows that it is typical of the mechanics involved and independent of the accidental variations in the thickness and properties of the materials of the shell.

The fracture pattern produced in glass spheres by allowing water to freeze in them slowly, that is, in an atmosphere not far below freezing, may be illustrated by the specimen shown in Fig. 28. On one



Figs. 28a and *b*. Two views of a thin spherical glass shell fractured under tension caused by expansion of the interior (water freezing within). Note the "focal bar" in *A* and approximately antipodal to it the "segment" in *B*.
(W. H. Bucher, 1924)

side of the sphere (Fig. 28 *A*) a primary crack is seen to bifurcate at both ends. Each of the resulting branches bifurcates again. In a sphere of perfectly uniform thickness and absolutely homogeneous substance, the progress of bifurcation might perhaps be exactly symmetrical and uniform in rate. This might, perhaps, carry all branches

to a common focus on the opposite side. Even slight variations in thickness and physical properties of the shell must inevitably cause some branches to grow in advance of others and must also cause them to be more or less deflected. The result must inevitably be something comparable to what is seen on the reverse side of the sphere here

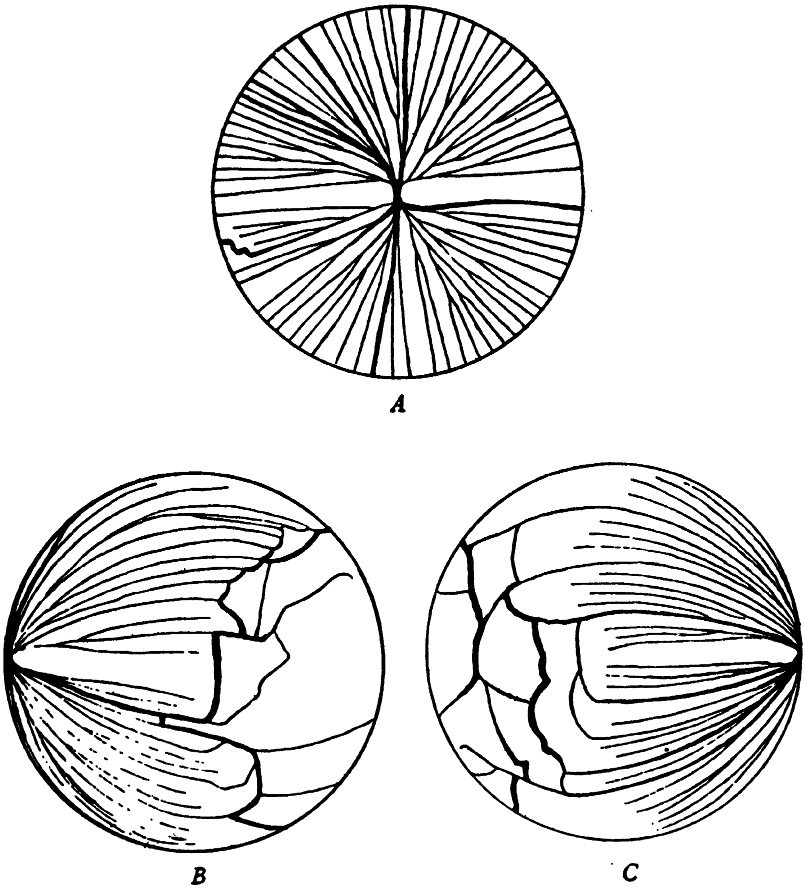


Fig. 29. Three views of a thin spherical glass shell fractured under tension caused by water freezing in it. Compare with Fig. 28. The pattern is the same in principle. The difference is due to more rapid freezing. While many cracks formed at first, only a few took up the actual enlargement of the surface (heavy lines). These form gaping fissures sealed by protruding ridges of ice.

(W. H. Bucher, 1924)

figured (Fig. 28*B*). A few branches have swerved and cut off the others, surrounding an irregular larger area. The presence of long, branching fractures[98] and the contrast of the two sides are the outstanding properties of this fracture pattern. They are also the outstanding properties of the pattern of the earth's mobile belts. Let us express the contrast of the two sides by speaking of a "focal bar" on one side and a "segment" on the other.

Fig. 29 illustrates the modification of the pattern that results from rapid freezing in very cold weather. Here the "focal bar" has been greatly shortened, almost reduced to a "focal point." A very large number of closely spaced cracks have formed by frequent bifurcation at small angles. But the great majority of these have not widened under continued expansion. They would be invisible but for the reflection of light on their surfaces seen through the glass. The few gaping cracks along which alone widening has taken place are drawn as heavy lines in Fig. 29. The side of the segment is unusually developed. Cracks have cut across from one to the other in abrupt arcuate cross-fractures. In the northeast quadrant of Fig. 29*B*, there is a beautiful festoon of arcs which reminds one of the Asiatic island festoons. South of the center lies a hairpin curve where one of the main branches running east from the "focal point" meets the boundary of the "segment." This is exactly the sort of relation that Staub especially postulated for the Antilles and their counterpart at the southern end of South America.

All the patterns developed in a large number of experiments with glass spheres lay between the types here figured. When paraffin spheres were subjected to tension by allowing water to freeze in them, the same pattern developed, a "focal bar" or "focal point" on one side and an irregular "segment" on the other. The greater lack of uniformity of material and the variable thickness of the shell caused considerable irregularities in the pattern. A typical example is shown in Fig. 30. Here the "segment" is a rather narrow roughly rectangular area. But it still occupies the characteristic position roughly opposite the "focal point" on the other side. In all paraffin

[98] Compare also Erich Seidl, *Bruch- und Fliess-Formen der technischen Mechanik und ihre Anwendung auf Geologie und Bergbau*, Band III, "Zerreiss-Form," VDI-Verlag, Berlin, 1930, Pl. 20, Figs. 1 and 2.

spheres the number of fractures was small compared with that of the glass spheres, which was probably due to the lower degree of brittleness. This may be inferred from experiments made by Duparc and

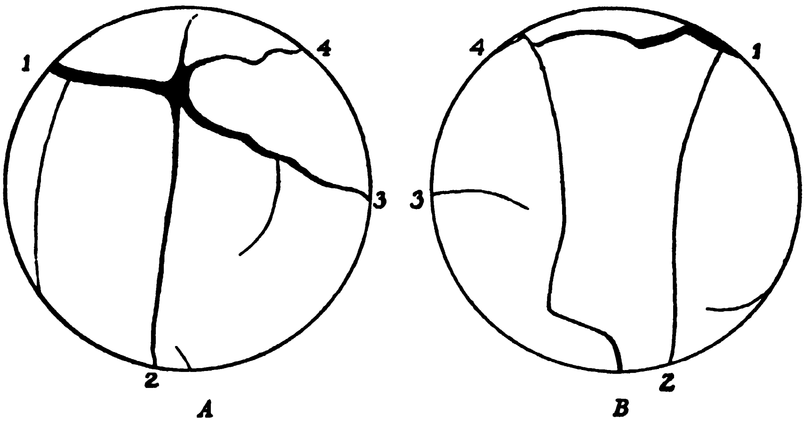


Fig. 30. Two views of a thin spherical paraffin shell fractured under tension caused by expansion of the interior (freezing water). Note the "focal bar" on one side and the "segment" on the other.
(W. H. Bucher, 1924)

Le Royer,[94] who repeated Daubrée's famous experiments on torsion cracks. When they increased the thickness of the glass plates used in their experiments, the number of cracks was greatly increased. But when they substituted terra cotta plates of similar dimensions but of a lower degree of brittleness, they obtained only a few cracks.

We are now ready to summarize the outcome of these experiments in the form of a definite opinion.

Opinion 14a. The pattern of fractures produced in a thin spherical shell by tensional stresses due to the expansion of the subcrustal interior resembles, in general as well as in its details (deflections, virgations and syntaxis, linkage), that of the Mesozoic-Cenozoic geosynclines and the ensemble of modern welts (newly folded as well as rejuvenated welts), the Hindukush-Pamir region representing the "focal bar" and the Pacific Ocean the "segment."

[94] Duparc and A. Le Royer, "Contributions a l'étude expérimentale des diaclases produites par torsion," *Arch. sci. phys. nat.*, Genève, 3me sér., Vol. 22, 1889, p. 307.

Opinion 14b. The pattern of welts produced in a weak spherical shell by compressional stresses due to the contraction of the subcrustal interior resembles that of the most active orogenic belts of Cenozoic time, the Mediterranean and circum-Pacific belts, with the high plateaus of the Peruvian and Bolivian Andes and those of the Pamirs and of Tibet representing approximately antipodal "nodes."

CHAPTER V

THE DIASTROPHIC CYCLE

"Il se flattait d'être sans préjugés, et cette prétention était à elle seule un gros préjugé."
Anatole France in *Le Crime de Sylvestre Bonnard.*

1. The Two Phases of the Diastrophic Cycle

The double resemblance expressed in opinions 14*a* and *b* would be neatly explained if world-wide crustal tension created the pattern of geosynclinal furrows and if later crustal compression transformed it according to its own laws. The geosynclines would form convenient zones of weakness where the folding would become localized, largely along the fewer belts needed to relieve the compressional stress.

The writer is convinced that there are several major facts of crustal deformation which combined demand such an assumption. These will be introduced one by one in following chapters. The evidence presented in this chapter is the least compelling. But it serves well to introduce the hypothesis.

The essence of the hypothesis is that epochs of crustal tension have alternated with epochs of crustal compression. It substitutes a dualism for the monistic views which consider one continuous process (such as contraction or westward drifting of continents) as the cause of all crustal deformation.

In our day of wholesome suspicion of all dualistic thinking the mere word "dualism" is sufficient to close some minds to further argument. It may be well to remind such sensitive critics that the rhythmic opening and closing of the lid of a singing teakettle is caused by one continuous process: the uniform liberation of steam. Similarly, should a rhythmic alternation of expansion and contraction of the crust prove a necessary, or at least the most plausible, inference from the facts, there may still be found back of it as continuous a single cause as any monistically-minded man may desire.

First we must ask ourselves: Is there anything in the progress of orogenic deformation that warrants the assumption of an alternation of tension and compression? This leads us at once to the broadest generalization concerning orogenesis.

Law 20. The typical orogenic cycle begins with geosynclinal depression and ends with a major uplift. The interval between these limiting events comprises two phases. The first phase is one essentially of quiet sinking, only occasionally interrupted by uplifts; the second phase consists of crustal foldings separated by diminishing epochs of renewed geosynclinal sinking.

2. Three Examples

The Upper Cretaceous geosyncline of the southern and central Rocky Mountain regions. Three examples may serve to illustrate this law. The first is that of the Upper Cretaceous geosyncline of the Rocky Mountain region. Beginning in Dakota (= Cenomanian) time, the broad "furrow" of this epeiric sea spread from Texas to the Arctic Ocean. We shall limit our brief description to the region about the central and southern Rocky Mountains, which have served us as illustrations before. From western Iowa and Minnesota, from Nebraska and Kansas westward to the edge of the Great Basin, we find the deposits of this inland sea. From a thickness of a few hundred feet in the east, they thicken to something like ten thousand feet in central Wyoming and the Great Plains. Locally, in southwestern Wyoming especially, even greater thicknesses are reported, going as high as twenty thousand feet and over. The main body of this geosynclinal series consists of argillaceous and fine-grained arenaceous sediments. Toward the east and southeast, limestones and chalk (from a few hundred to over a thousand feet thick) are a conspicuous part of the lower portion of the system.

They serve to emphasize the disparity between the east and west sides of the geosyncline. Coarser sediments are largely missing on the eastern side, toward the old continental shield. Toward the western and southwestern margin, on the other hand, coarser detrital sediments increase in importance.

Here the encroaching sea encountered, in what is today Colorado and New Mexico and in adjoining regions, scattered residual uplands, remnants of an orogenic movement which in later Paleozoic time had created the "ancestral Rocky Mountains."[1] Wrapping

[1] W. T. Lee, "Early Mesozoic Physiography of the Southern Rocky Mountains," *Smithsonian Misc. Coll.*, Vol. 69, No. 4, 1918, pp. 1-41; *idem*, "Building of the Southern Rocky Mountains," *Bull. Geol. Soc. America*, Vol. 34, 1923, p. 288; F. A. Melton, "The Ancestral Rocky Mountains of Colorado and New Mexico," *Jour.*

around these older highlands[2] and extending to the western shores, coarser detrital marine sediments were spread, intercalated more and more with brackish and freshwater formations including coal beds, as the western shores are approached. Numerous stratigraphic data obtained by members of the U.S. Geological Survey in connection with the systematic study of the coal fields of Utah, Arizona, Colorado, and New Mexico, give an excellent picture of this interfingering of marine and terrestrial sediments in the western regions of the geosyncline.

On the whole, the western shore of the Cretaceous geosyncline was relatively low and flat, with coastal swamps. The sediments brought down from the degrading uplands to the west, at first were spread eastward largely by waves and marine currents and later were built out in growing alluvial plains.

While these sandstones in the western part are coarse in comparison with the silts and shales of the broad central part of the geosyncline, they do not indicate the nearness of mountains. Their physical character and interfingering with the finer-grained exclusively marine sediments farther from the former shore are, in fact, entirely comparable with the similar relations existing in the sediments of the Gulf-coast Cretaceous and Tertiary formations in the vicinity of the Mississippi embayment. It is instructive to compare Lee's section showing the sediments of the Rocky Mountain geosyncline[3] with Shaw's section of the coastal plain in Mississippi.[4]

Geol., Vol. 33, 1925, pp. 84-90; W. A. VerWiebe, "Ancestral Rocky Mountains," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 14, 1930, pp. 765-88; Charles Schuchert, "Ancestral Rocky Mountains and Siouis," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 14, 1930, pp. 1224-7.

[2] J. Harlan Johnson and Harry A. Aurand, "A Preliminary Contribution to the Benton Paleogeography of Eastern Colorado," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 13, 1929, pp. 850-3; T. S. Lovering, "Geologic History of the Front Ranges," *Proc. Colorado Sci. Soc.*, May 1929.

[3] See, e.g., the semi-diagrammatic section, from east of the Denver Basin to west of the Colob Plateau of Utah, in Willis T. Lee, "Relation of the Cretaceous Formations to the Rocky Mountains in Colorado and New Mexico," *U.S. Geol. Survey, Prof. Paper 95*, 1915, p. 29, Fig. 12; also Fig. 3, p. 444 in E. M. Spieker and John B. Reeside, "Cretaceous and Tertiary Formations of the Wasatch Plateau, Utah," *Bull. Geol. Soc. America*, Vol. 36, 1925.

[4] E. W. Shaw, "The Pliocene History of Northern and Central Mississippi," *U.S. Geol. Survey, Prof. Paper 108*, 1918, Pl. 45, opp. p. 126.

The story of the migrations of the strand line in the Gulf area[5] *practically duplicates that of the western part of the interior Cretaceous seas.* Even the spreading of the highly variable "Orange Sands" of the Citronelle formation with lenses of conglomerate and variegated clays which ended (for the present) the marine transgressions, has its counterpart in the spreading of the sands and varicolored dominantly red shales of the Wasatch formation of Utah.[6] There is nothing in the record of deposition on the western shore of the Cretaceous Interior Sea which calls for upward movements of orogenic character or for uplifts of an order of magnitude different from those which furnished the sediments of the Gulf coastal plain during Cretaceous and Tertiary times.

The evidence is furthermore sufficient to prove that the present ranges of the southern Rocky Mountains did not rise as mountains during the geosynclinal epoch and that at least a part of the Upper Cretaceous formations extended across the present mountains.[7] The same seems to be true for the United States portion, at least, of the northern Rocky Mountains.[8]

A large part of the Upper Cretaceous sediments in the main portion of the geosynclinal trough consisted of fine-grained sediments, even in the western part where the nearness to shores introduced wedges of sandstones during epochs of regression. Far out, in the

[5] See E. W. Berry, "Erosion Intervals in the Eocene of the Mississippi Embayment," *U.S. Geol. Survey, Prof. Paper 95,* pp. 73-83 (note esp. diagram par. 27, p. 74); L. W. Stephenson, "Major Marine Transgressions and Regressions and Structural Features of the Gulf Coastal Plain," *Am. Jour. Sci.,* 5th ser., Vol. 16, 1928, pp. 281-98. (Maps on which non-marine sediments are shown separately.)

[6] "Geologists . . . have repeatedly emphasized the great variability of the Wasatch formation, stating that hardly any two sections of the rocks, even if taken not far from one another, are alike." E. W. Spieker and J. B. Reeside, *op. cit.,* p. 448. Compare the details of the description following this quotation with that given in G. C. Matson and E. W. Berry, "The Pliocene Citronelle Formation of the Gulf Coastal Plain and Its Flora," *U.S. Geol. Survey, Prof. Paper 98,* 1916, pp. 167-204.

[7] Willis T. Lee, *op. cit., U.S. Geol. Survey, Prof. Paper 95,* 1915, esp. pp. 34-6; also "Building of the Southern Rocky Mountains," *Bull. Geol. Soc. America,* Vol. 34, 1923, p. 288. For evidence qualifying Lee's conclusions see earlier footnotes.

[8] See, e.g., F. L. Ransome, "The Tertiary Orogeny of the North American Cordillera and Its Problems," in *Problems of American Geology,* Silliman Memorial Lectures, Yale University Press, 1915, p. 322.

central region of the trough, fine-grained sediments dominated. In northeastern Wyoming, for instance, more than nine-tenths of the Upper Cretaceous rocks, which reach a total thickness of over 5,400 feet, are fine-grained shales, sandstones, and calcareous marls.[9] In northwestern Colorado, west of the Rocky Mountain axis, the lower part of the Upper Cretaceous sediments consists of about 5,000 feet of shales, mostly "soft dark gray to drab clay shales," the "Mancos shale" with but a few insignificant sandy zones. In the overlying 4,500 feet of Cretaceous coal-bearing beds, sandy sediments dominate, and yet almost one-third this thickness is occupied by the dominantly shaly formation of the "Lewis Shale."[10]

Even still farther west, in the region of the Wasatch plateau coal field, a total of over 4,000 feet in the lower part of the Cretaceous section consists of marine shales ("Mancos shale") out of a total of over 10,000 feet of sediments becoming progressively more sandy toward the top.[11] The uniform petrographic character of these sediments indicates that important reversals and disturbances did not occur while they were laid down. It is this evidence of general sinking without important orogenic movements to depths allowing the accumulation of two miles of sediment, all within one period, that marks the Colorado sea as a typical geosyncline.[12]

Layers of volcanic tuff, bentonite, form a characteristic feature of this geosynclinal shale series in the Rocky Mountain Cretaceous, from Montana[13] to New Mexico. Only recently the presence of much

[9] W. W. Rubey, "Lithologic Studies of Fine-Grained Upper Cretaceous Sedimentary Rocks of the Black Hills Region," *U.S. Geol. Survey, Prof. Paper 165,* pp. 1-54.

[10] E. T. Hancock, "Geology and Coal Resources of the Axial and Monument Butte Quadrangles, Moffat Co., Colorado," *U.S. Geol. Survey, Bull. 757,* 1925, pp. 6-7.

[11] E. M. Spieker, "The Wasatch Plateau Coal Field, Utah," *U.S. Geol. Survey, Bull. 819,* 1931, p. 16.

[12] European writers, as for instance Argand and Staub, speak of the Rocky Mountains, especially their southern division, as folds radically different in origin from folds connected with geosynclines. We shall endeavor in the following to show that this view is not valid.

[13] Volcanic tuff may also exist as a constituent of some of the shales. Concerning the peculiar lithologic character of the Mowry shale, for instance, see E. G. Robinson, "Some Notes on the Upper Cretaceous Paleogeography of Montana," *Bull. Am. Assoc. Petrol. Geol.,* Vol. 8, 1924, p. 556; W. W. Rubey, "The Origin of the Mowry Shale," *Jour. Washington Acad. Sci.,* Vol. 17, 1927, p. 235.

volcanic material in the Cretaceous sediments of the Gulf coast[14] has become known.

When the change came from this quiet epoch of sinking to the first epoch of crustal folding, in the course of this first deformation locally large quantities of andesite were poured out. Few, if any, certain remnants of these flows are preserved today, but when sinking was resumed after the orogenic spasm, andesitic débris formed a large part of the thick and coarse early Tertiary beds of the Denver basin and corresponding formations.

Before the orogenic movement had assumed large proportions, the sea had largely been forced out of the geosynclinal trough and coarser terrestrial (coal-bearing) beds spread far and wide in it. But only after the orogenic phase had gotten well under way, do we see in the sediments of this region the presence of relatively high welts yielding conglomerates and coarse sandstones into the newly sinking depressions. Unconformities and coarse sediments mark repeated spasms after the first. As far as can be told, the new ranges arose in the western half of the geosynclinal belt which bordered the older land, the source of most of the sediments.

From the beginning and throughout the orogenic phase, deformation tended to follow the structure lines inherited from the late Paleozoic orogeny. In this feature as well as in the presence of volcanic action during the geosynclinal phase, the Rocky Mountain region differs from the Appalachians and the Western Alps, the other examples to be discussed. The nature of this difference will be taken up in a later chapter (Chapter x).

The fundamental difference between the geosynclinal and the orogenic phase stands out clearly. In the former, the whole belt sinks,

[14] Beds of lithic and vitric tuffs, one reaching a thickness of 125 feet or more, occur in the Bingen formation (of Turonian age) over a distance of 115 miles in southwestern Arkansas and southeastern Oklahoma. Tuffs and flows of similar age occur in the Monroe gas field of Louisiana. Bentonite is found in Louisiana, also in beds younger than the Bingen formation. Volcanic ash beds also occur in the Eagle ford shale of northeastern Texas and above the Austin chalk near Austin, and even west of San Antonio. (Quoted from H. D. Miser and Clarence S. Ross, "Volcanic Rocks in the Upper Cretaceous of Southwestern Arkansas and Southeastern Oklahoma," *Am. Jour. Sci.*, 5th ser., Vol. 9, 1925, pp. 113-26.) In the Lytton Springs oil field (Caldwell County), Texas, a mass of serpentine lies beneath the Austin chalk in the shape of an old volcanic cone, interfingering in places with the Austin chalk (D. M. Collingwood and R. E. Rettger, "The Lytton Springs Oil Field, Caldwell Co., Texas," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 10, 1926, pp. 953 *ff*.).

receiving fine-grained sediments, without evidence of any larger orogenic upward movement.[15] In the latter, upward movement drains the furrow, fills it with sediments and in the end lifts the mountain axes without creating corresponding furrows. Today axes of uplift and sediment-filled basins alike stand high above sea level and are undergoing erosion.

The Appalachian Geosyncline. We now turn to the second of our illustrations, the prototype of geosynclines, that of the Appalachian region. We shall limit our brief remarks to the Appalachian geosyncline in the restricted sense, as proposed by Schuchert,[16] that is, to that part which lies south of Vermont. Here we find in the coarse clastics of the Lower Cambrian the echoes of the last Proterozoic orogenic movements. As they die away, the early Paleozoic geosynclinal phase begins to stand out clearly. It is the time of widespread carbonates, of the famous Cambro-Ordovician limestones, such as the Shenandoah group which reaches a thickness of 6,800 feet in central southern Pennsylvania,[17] and the "Knox Dolomite" of similar thickness, overlain by one to two thousand feet of Chicamauga limestone, in eastern Tennessee. These are followed over wide areas by one to several thousand feet of graptolite shales (Martinsburg and equivalent formations). These resemble greatly the graptolite shales of Scandinavia. They seem to represent a facies which may well be compared with the dark marine shales in the lower part of the Cretaceous Rocky Mountain geosyncline. After these appear the coarser clastics which herald the first orogenic paroxysm. No comparable thickness of carbonates formed again. In the great Upper Devonian series of marine shales which center in eastern Pennsylvania we have the record of another climax of geosynclinal sinking. The alluvial beds (here terrestrial red beds) pushed across the old seaway quite as the Laramie and subsequent Paleocene beds spread across the sediments of the marine shales of the Montana series. After that, upward movements and terrestrial sediments soon dominate,

[15] Minor episodes of uplift (along old structural lines) are found here as in other similar geosynclinal regions, as stated specifically in law 20.

[16] Ch. Schuchert, "Sites and Nature of the North American Geosynclines," *Bull. Geol. Soc. America,* Vol. 34, 1923, p. 172. (Schuchert distinguishes the part north of Massachusetts as the "Saint Lawrence Sea," using the term introduced by Canadian geologists.)

[17] M. Grace Wilmarth, "Tentative Correlation of the Named Geologic Units of Pennsylvania" (chart), *U.S. Geol. Survey,* April 5, 1928.

leading to the great orogenic disturbances toward the end of the Paleozoic.

We shall not concern ourselves here with the several orogenic cycles, the repeated alternations of times of dominant sinking and of relatively abrupt uplifts. For our purposes the broader aspects of the supercycle of the whole of Paleozoic time is of chief interest. The first larger phase is that of the great early Paleozoic limestones and marine shales. Here again we see a furrow sinking to a depth of over a mile without a corresponding welt arising on its side. Again the source of the clastics that pour into the furrow is not the old stable land mass of Laurentia, but the unstable land in the direction of the earlier Algonkian orogenic belt to the east. It is, of course, impossible to say where the eastern shore of the Cambro-Ordovician sea lay. Outcrops exist east of the Blue Ridge, from Chester Valley, west of Philadelphia, to Frederick, Md. In the slate belts of Virginia, Ordovician fossils were found by Darton[18] in the Arvonia quarries in Buckingham County and in the Quantico slates in Prince William County. Bassler seems inclined to ascribe a Chazy age[19] to these beds rather than a Cincinnatian age, as thought at first. Ordovician rocks may be among the infolded post-Algonkian rocks farther south. The metamorphism of such sharply infolded synclines ("Cambrian") as are seen in the Mt. Mitchell region of North Carolina and in the Kings Mountain district of North and South Carolina, suggests at least that a considerable thickness of higher sediments existed. It appears probable that the shore of the earlier Ordovician geosyncline lay well to the east of the present Blue Ridge. Yet it is quite clear that embryonic ranges which formed as a result of the first post-Cambrian orogenic deformation arose in the eastern half of the Ordovician geosyncline. Here again, this is the side adjacent to the welts that had formed in the earlier orogenic cycle, that is, the belt of earlier mobility and not on the side of the old stable foreland. In spite of the different scale, both in space and in time, the analogy to the

[18] N. H. Darton, "Fossils in the 'Archean' Rocks of Central Piedmont Virginia," *Amer. Jour. Sci.*, 3rd ser., Vol. 44, 1892, pp. 50-2; N. H. Darton, *Fredericksburg Folio, U.S. Geol. Survey, Geol. Atlas, No. 13*, 1894; T. L. Watson, *Mineral Resources of Virginia*, Lynchburg, 1907, p. 42; T. L. Watson and S. L. Powell, "Fossil Evidence of the Age of the Virginia Piedmont States," *Am. Jour. Sci.*, 4th ser., Vol. 31, 1911, pp. 33-44.

[19] A. I. Jonas, "Geological Reconnaissance in the Piedmont of Virginia," *Bull. Geol. Sci. America*, Vol. 38, 1927, p. 842, n. 8.

Colorado geosyncline is noteworthy. As far as is known at present, volcanic activity was practically absent from the Appalachian geosyncline (*sensu stricto*).[20] When the orogenic phase reached its end in the "Appalachian revolution," in later Permian or early Triassic time, the mountain welt rose without giving rise to a corresponding geosyncline in front of it. Erosion has prevailed in mountains and foreland alike during and since that orogenic crisis.

The Alpine Geosyncline. It is only with great reluctance that the writer introduces the Alpine geosyncline as his last illustration. It is to the European literature what the Appalachian is in North American geology, and can, therefore, not well be omitted from an attempt to quote representative examples. In contrast to the Appalachians, however, the Alpine geosyncline is so intricately disturbed that a most complicated process of unravelling of partly hypothetical structures is needed to restore the picture of the original sedimentary trough. It is not surprising that a great diversity of opinion exists as to the character of the geosyncline. To the American reader of Alpine geological literature, the constant emphasis on the inferred depths of the sea is surprising. This "geographical" concept of the geosyncline as a topographic submarine furrow led Albert Heim, in his classical *Geologie der Schweiz*, to a most skeptical attitude toward the concept. He says,[21] a geosyncline is said "to be a zonal basin of deposition continuous during several periods, with littoral sediments at the margins, with neritic farther out, and with more and more abyssal deposits in the center. In addition, the geosynclines are supposed to be predestined to form folded mountains." As to the first part of this form of the concept, it is easy to show that in the Swiss Alps (and in other parts alike) this simple geographical concept did not apply during large parts of their Mesozoic and early Cenozoic history. As to the second part, the assumed rise of folds from the center of the geosynclinal basin, Heim is similarly skeptical. In the

[20] "Nelson's volcano" which spread its ashes (now bentonite) over the area of many States during Stones River and Lowville (Llandeilo and Caradoc) time, stood probably outside the geosynclinal trough. It may have borne a relation to the geosyncline similar to that which the gulf volcanoes bore to the Coloradoan geosyncline. (For a list of references to the Ordovician bentonite beds see C. S. Ross, "Altered Paleozoic Volcanic Materials and Their Recognition," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 12, pp. 149-50.)

[21] Alb. Heim, *Geologie der Schweiz*, Band 2, 2d H., Leipzig, 1922, p. 871 (free translation).

Alps, as in other folded regions, it seemed to him that the folds arose from one side of the geosynclinal basin rather than from its center.

In these lectures we have taken pains to avoid the "geographical" concept of a geosyncline which goes back to Haug's classical paper of 1900.[22] From our point of view the great variations in facies that are found in the Alps are but natural and correspond entirely to the observations in our simpler Appalachian belt.

The earlier diagrammatic concept of a uniform Alpine geosyncline was sharply and most radically attacked by Deeke[23] who showed the dubious nature of some of the evidence of the deep-sea origin of many of the "bathyal" and "abyssal" sediments (ammonite shales, Aptychus shales, radiolarites) and of other assignments of depth relations in Alpine regions. His attempt to refer the complexity of Alpine structure to the compression of an archipelago of horst-like islands between graben-like troughs goes unquestionably too far. The basic concept, however, of depths varying at right angles to the strike, of shallower belts, possibly of islands undergoing erosion, and deeper ones, receiving greater and partly local sediments, is proving more and more correct. Argand[24] and Staub[25] have shown that it is probable that "embryonic folds" arose in the later Mesozoic seas of the Alpine geosyncline.[26]

American students will recognize in these "embryonic folds" of the Alpine geosyncline the counterparts to the subparallel "barriers" that divided the Appalachian syncline into distinct marine troughs already in the earlier Paleozoic.[27] Ulrich and Schuchert interpreted these barriers as rising folds that were apparently more or less prescribed by an earlier orogenic cycle, and as the parent welts which were to develop later into the great zones of overthrusting of the

[22] E. Haug, "Les géosynclinaux et les aires continentales," *Bull. Soc. Géol. France*, 3e sér., Vol. 28, 1900, pp. 617-711.

[23] W. Deeke, "Die alpine Geosynclinale," *N. Jahrb. f. Min.*, Beil. Band 33, 1912, pp. 831 *ff.*

[24] E. Argand, "Sur l'arc des Alpes occidentales," *Eclogae geol. Helvet.*, Vol. 14, 1916.

[25] R. Staub, "Ueber Faziesverteilung und Orogenese in den südöstlichen schweizer Alpen," *Beitr. z. Geol., Karte d. Schweiz*, Vol. 46, 1917.

[26] See also pp. 20-2.

[27] E. O. Ulrich and Charles Schuchert, "Paleozoic Seas and Barriers in Eastern North America," *New York State Mus., Bull. 52*, 1902, pp. 633-63.

final folded structure. This is precisely the view at which both Argand and Staub arrived independently from their studies in the western and eastern Central Alps of Switzerland respectively[28] for the rôle which their "embryonic" folds played in the development of Alpine structure.

In spite of the much greater complications in the Alps, other parallels are recognizable with the two American examples given above. Let us turn back to the facies studies of Arnold Heim, to which we referred in the first chapter. He showed that in the Swiss sections of the Mesozoic the changes of facies are rapid at right angles to the strike, while along the strike the facies remain constant or change gradually over considerable distances. This is, of course, characteristic of "furrows" in general. The original arrangement of the autochthonous facies in the eastern Swiss Alps, as described by Arnold Heim, serves to bring out more interesting relations. In the north, relatively thin deposits of the Triassic and Lower and Middle Jurassic are seen overlapping and burying higher parts of the old land surface.[29] Farther south the sediments of the same age are represented by the "Bündnerschiefer" (= "schistes lustrés"). These are argillaceous rocks which, where little altered by metamorphism, appear as dark, often black slaty shales with more calcareous and again more sandy layers. Mostly they are altered to graphitic slates, phyllites, and so forth. It is impossible to determine the original thickness of these intricately kneaded and crumpled schistose rocks. But it certainly reached 10,000 feet and locally may have been as high as 15,000 feet.[30] Now this arrangement is quite comparable to that of the Colo-

[28] The presence of longitudinal "barriers" in the Western Alps was emphasized earlier by E. Haug, "L'origine des Préalpes Romandes et les zones de sédimentation des Alpes de Suisse et de Savoie," *Arch. sci. phys. et nat.*, 3e sér., Vol. 32, 1894, pp. 154-73.

The existence of rising, anticlinal belts, within geosynclines, was elaborated and made part of a broader concept of geosynclinal instability by P. Arbenz. ("Probleme der Sedimentation und ihre Beziehungen zur Gebirgsbildung in den Alpen," *Festschrift Alb. Heim*, 1919.) For a brief critical survey of the problems of facies in the Alpine geosyncline, see also S. von Bubnoff, *Die Grundlagen der Deckentheorie in den Alpen*, Stuttgart, 1921, pp. 99-110. A valuable sketch of sediments within the whole Alpine geosynclinal belt was recently given by H. P. Cornelius, "Zur Vorgeschichte d. Alpenfaltung,' *Geol. Rundschau*, Vol. 16, 1925, pp. 350-77; 417-34.

[29] See, e.g., Fig. 70, p. 284, of Alb. Heim, *Geologie der Schweiz*, Vol. II. (The Transgressions on Windgälle Mountains.)

[30] Alb. Heim, *Geologie der Schweiz*, Vol. II, 1922, p. 497.

rado geosyncline: thin, dominantly calcareous beds on the side of the old land; thick, more or less bituminous argillaceous beds on the side toward the site of the older orogenic cycle. The fine clay substance is so widely and uniformly distributed that it seems to be the waste from the older land rather than from rising welts. The latter have furnished locally different, coarser material, as we have indicated before when speaking of the embryonic folds.

The evidence of dominant sinking and the absence of indications of a corresponding rise of welts is the chief point of value for our present inquiry. In the Upper Jurassic the evidence becomes even more convincing. At that time the supply of even the fine clastic materials ceased completely. In the northern region the Upper Jurassic is developed chiefly as the dense, light to dark gray "Hochgebirgskalk" ("Quintner Kalk"), 600 to 2,000 feet thick,[31] which forms the most imposing cliffs of the Helvetic Alps. In the southern part of the Alpine geosyncline the Upper Jurassic (and in part even the Middle Jurassic) is chiefly represented by radiolarites with red (and green) shales (besides subordinate limestones). Whether these radiolarites are deep-sea sediments or not, they at least show strikingly the sinking of the geosyncline without the corresponding rise of welts.

In the upper Malm the first Mesozoic orogenic spasms created the "embryonic folds" with the corresponding breccias (on the north sides of the folds only) (see p. 20). In the Cretaceous, we see a corresponding sequence of events. On page 21, in Fig. 6 we have given Arnold Heim's reconstruction of the original distribution of facies during the Lower Cretaceous, at right angles to the strike of the eastern Helvetic geosyncline. The change from thin, dominantly calcareous sediments in the north to thick, argillaceous sediments in the south is equally striking. At the end of the Lower Cretaceous time the pure, dense limestone of the "Schrattenkalk" facies spread over the whole width of the Helvetic sedimentary basin.[32]

In the Upper Cretaceous the Seewerkalk, a light gray, dense limestone, forms the chief sediment. It is 300 to 600 feet thick.[33]

[31] Alb. Heim, *Geologie der Schweiz,* Vol. II, 1922, pp. 153, 287.
[32] In the northern half this facies reaches thicknesses of 600 to 1,000 feet. (Alb. Heim, *op. cit.,* Vol. II, p. 306.)
[33] Alb. Heim, *op. cit.,* p. 315.

These thick limestones, such as the "Hochgebirgskalk," the "Schrattenkalk," the "Seewerkalk," seem petrographically the counterpart to the Cambro-Ordovician limestones. The Cretaceous limestones of the Helvetic *decken* in the Alps are rich in Foraminifera. This has led to their interpretation as deep-sea sediments.[34] The presence of these great thicknesses of limestones relatively free from clastics shows that the geosynclinal phase produced sinking measured by thousands of feet without a corresponding rise and influx of clastics. The majestic limestones of the Eastern Alps bear this out for the earlier geosynclinal "furrow" of Triassic times, when the region of the Swiss Alps still formed part of the inundated northern foreland.

Like the Appalachians, the Alpine Mesozoic geosynclinal belt was largely devoid of volcanic activity. It seems that the basic igneous rocks of the Penninic zone were largely intrusive. We shall refer to them later (page 268).

The last orogenic movements displaced the lingering remnants of the sea from the foreland, folded and displaced the coarse clastics that had piled up in front of the rising mountains, lifting both mountains and foreland high above the sea leaving both a prey to the forces of erosion.

3. Minor Epochs within the Phases

The examples presented in the preceding chapter are sufficiently representative to bear out the validity of law 20. They show that the typical product of the geosynclinal phase is a furrow, more or less filled with sediment, without an adjoining mountain range, and that when the orogenic phase comes to an end, it leaves a welt without an accompanying furrow. In one the downward movement dominates, in the other the upward movement.

Besides contrasting the two major phases, law 20 refers to interruptions, minor epochs within each phase, in which the normal movement of the phase is reversed. The evidence for these reversals is clearest in the case of the geosynclinal phase.

At least in their near-shore facies, all geosynclinal sediments show abundant and clear records of regressions and transgressions, of alternating shallowing and deepening of the sea, such as faunal

[34] Alb. Heim, *op. cit.*, Vol. II, p. 315.

disconformities, true erosion unconformities, intercalations of coarser sediments, tongues of terrestrial deposits, etc.

It should be remembered that the oscillations of sea level thus recorded are the result of two factors which may be independent of each other: diastrophism and changes in world climate. The latter cause corresponding changes in the level of the sea chiefly by altering the quantity of ice stored at the poles. Yet the local character of many of the oscillations of sea level within geosynclinal belts shows plainly that diastrophic pulses had an important share in bringing them about.

That upward movements of the adjoining lands must have played an important rôle during the geosynclinal phase, is indicated by the great thickness of the essentially fine-grained clastics that fill many of the geosynclines in their early stages. The width of the North American Cretaceous epeiric sea, in latitude 42° N., was over eight hundred miles, as described above. The floor of this sea sank to the greatest depths in its western part and from this side also much of the sediment, certainly most of the sandy materials, were derived. To be sure, the eastern shore must have contributed its share as it did to the Cretaceous deposits of the central and eastern Gulf coasts. Some sediment was also furnished by contemporaneous volcanic activity. Yet, most of the materials that make up the thick stratigraphic column in the western half must have been derived from the degradation of the land to the west.

In the same latitude, this adjoining land was only about five hundred miles wide. Let us assume, for the sake of argument, that four hundred miles of the width of the western land mass drained eastward into the epeiric sea and that the sediment derived from these four hundred miles was spread over an equal width of sea floor, to a thickness of somewhere between one and two miles. This means that at the very least a similar thickness of rock was eroded on the average from every unit of the land surface. Since our assumptions were made in such a way as to give minimum results, the land mass removed by erosion may have been twice or several times as high.

The nature of the sediments, however, shows that no mountain mass such as these estimates suggest existed along the western shore during the earlier, geosynclinal, phase. The conclusion seems inevitable, then, that either continuous or repeated uplift of the western land kept up the supply of fine rock waste which filled the geosyncline.

4. Interpretation

The hypothesis. It has become customary to think of the rising of the sediment-furnishing land and the sinking of the sediment-receiving sea floor as simultaneous and continuous. The writer proposes as an alternative view that the two processes are alternate and repetitive.

In the current view, the rising welt is pictured as pushing on top of the adjoining part of the crust and bending it down, thus forming the foredeep. Closer scrutiny causes one to doubt if this view is adequate. If the crust is as strong as we have reason to believe (pages 33-6), a mountain range at least several thousand feet in height is required to produce the desired effect. This range must rise sharply on the edge of the foredeep to produce the necessary bending moment. But such a mountain did not exist, as the sediments show in the examples just discussed. Furthermore, it is clearly impossible, mechanically, to picture a belt hundreds of miles wide as due to a bending moment introduced by an excess weight applied at one end, as, for instance, in the case of the Colorado geosyncline.

We cannot dismiss this illustration as inappropriate, claiming that the Cretaceous epeiric sea was not a typical geosyncline. No one knows what a "typical geosyncline" should look like. The Cretaceous formations occupy an elongated belt in which sediments accumulated to abnormal thickness and from a part of which folded and thrust-faulted[35] mountains have risen. Our problem is to account for this fact, irrespective of any nomenclature.

Some will object that the writer is confusing the results of "orogenic" and "epeirogenic" deformation. Such an objection arises from preconceived views concerning the relation of these two types of crustal deformation. The writer hopes to show in these pages that it is possible to arrive at a consistent view concerning this relation by the path of reasoning here used. He would ask the reader to follow him, deferring judgment to the end of the second last chapter which will be devoted to epeirogenesis. By the definition introduced at the beginning, we call all deformations "orogenic" which produce vertical displacement in narrow, long zones with amplitudes in excess of those realized in vertical movements of broad areas.

[35] See later, pp. 162-9.

The hypothesis of alternating tensional and compressive stresses in the crust is here proposed as a possible explanation for the facts summed up in laws 16 to 20. Folding and upward movements are thought to be the result of compression, and fracturing and downward movements that of tension.

We assume by way of hypothesis that when a portion of the crust suffers tension, it responds in such a way that the surface of a relatively narrow belt becomes lowered with reference to the surrounding surface, forming a furrow which may be hundreds of miles wide. If it drops low enough, this will develop into a seaway. While tension lasts, the adjoining land is thought to remain passive.

The tensional stress is assumed to decrease eventually to zero. But the same process which brought it to an end is assumed to continue, producing compression in this part of the crust. Under compression, the furrow on the surface acts as a notch does in a beam. It creates a line of weakness. If the depression is asymmetrical in cross-section, the side with the sharper flexure is the line where the stresses are localized. Here the higher side tends to be bulged up in the form of a welt, during epochs of compression. While compression lasts, the adjoining furrow lies essentially passive.

After a lapse of time, the stresses are reversed and sinking is resumed under renewed tension, only to be followed again by compression and so on in ceaseless rhythm.

These minor epochs of tension and compression are assumed to combine into a large rhythm which finds expression in what we have called "phases" of diastrophism. During the geosynclinal (or "taphrogenic")[36] phase, the results of epochs of compression are small compared with those of epochs of tension. The furrows dominate the diastrophic picture. Peneplanation may reduce the relief of adjoining lands to such an extent that the clastic sediment yielded by them becomes insignificant, allowing deposits of carbonates (limestones and

[36] The term "taphrogeny" was coined by Krenkel to designate the origin of rift valleys through crustal tension. He pictures the tension as acting locally, not worldwide, as here assumed, and he thinks of rift valleys as not only structurally, but also genetically different from geosynclines. Since the hypothesis here proposed pictures all furrows as the result of crustal tension, the term "taphrogeny" may be extended to designate the opposite of "orogeny" in general, that is, the tensional phase at large. Not much use is made of the term in these pages, however. See E. Krenkel, *Die Bruchzonen Ostafrikas*, Berlin, 1922.

dolomites) or of silica (bedded cherts, radiolarites) to accumulate to great thicknesses, in the furrow.

In the later orogenic phase, the reverse is true. The effects of compression outstrip those of tension. Higher welts are formed in epochs of compression. Erosion cannot erase the welt formed in one epoch before compression sets in again. The welt rises to mountainous proportions. The juxtaposition of the high welt and the deep sediment-filled furrow leads to the violent deformation traditionally known as "revolutions." The dominant upward movement lifts the surface of the furrow above sea level.

When the broader rhythm of stresses introduces a new phase of dominant tension, a new furrow may form at a different site leaving the old belt essentially inactive, thus terminating its "life."

This, then, is the hypothetical picture the writer proposes to test. It was designed to satisfy the conditions expressed in laws 16, 17, and 20, without conflicting with the facts summed up in the other laws so far stated. The writer is prejudiced in its favor not because it is his own, but because he believes that other "laws," yet to be discussed, point in the same direction, and because he knows of no "laws" that are incompatible with it. The hypothesis may be stated concisely as follows:

Opinion 15a. The localization and sinking of the surface of furrows is the result of tensional yielding of the earth's crust. The rise of crustal folds is due to a compression of the crust. The deformation of the crust is the product of alternate action of tensional and compressive stresses.

Opinion 15b. Minor "epochs" alternately of tension and of compression combine into a larger rhythm of "phases," alternately of dominant tension and dominant compression.

Opinion 15c. This alternation of stresses in the crust is due to volume changes in the subcrustal body of the earth.

The last sentence of this "opinion" follows directly from opinions 13 and 14 (pp. 114, and 123-4), based on laws 17 to 19 (pp. 99-101).

The mechanical implications of the hypothesis. Something remains to be said about how we are to picture to ourselves the manner in which crustal tension causes furrows to form and how subcrustal volume changes may come about.

For over a century, geologists have made themselves acquainted with the effects of compression on layered materials. Only much more recently have they concerned themselves with the deformation of crystalline materials under compressive stress. Practically no attention has been paid, to this day, to the behavior of materials under tensional stress. We all lack mental pictures of what changes make their appearance when materials are put under tension. We must turn to the testing laboratories of our industries for our basic mental pictures and to the literature on the physics of materials for modern theory.

Most recently, Seidl has assembled pictures of some significant observations made in the course of technical tests in several small volumes entitled *Bruch- und Fliess-Formen der technischen Mechanik*. The third volume deals with the deformations produced by tearing.[87] The reader will find a careful study of this important work most profitable. Fundamental facts about the behavior of materials under tension may be learned from any text-book on the physics of materials. From two of these Fig. 31 and 32 are taken which illus-

Fig. 31. Flat steel rod deformed by tension to a point just short of rupture. The details of the deformation are shown by the coordinate lines etched into the steel before the experiment.

(After E. Seidl, 1930; reproduced from *Bruch- und Fliess-Formen der technische Mechanik*, by permission of VDI-Verlag.)

trate the well known behavior of a rod of non-brittle material (steel) under tension. Fig. 31[88] shows the permanent deformation induced in a flat bar of steel, when tension is stopped short of rupture. A pattern of rectangular lines was ruled on the rod before the test. Its deformation indicates the change in form produced by the tensional

[87] E. Seidl, *Bruch- und Fliess-Formen der technischen Mechanik*, VDI Verlag, Berlin NW7, 1930, Band III, "Zerreiss-Form."

[88] Reproduced from E. Seidl, *op. cit.*, p. 2, Fig. 1.

pull. Fig. 32[39] contrasts the behavior of non-brittle with that of brittle materials (steel and cast iron). In the graph above each diagram, the ordinate indicates the relative amount of lengthening from point to point along the length of the bar. In the non-brittle material

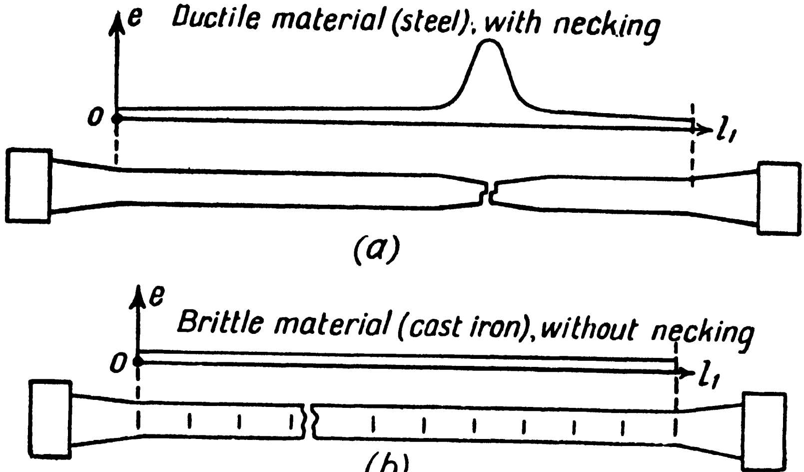


Fig. 32. Two diagrams contrasting the behavior of test bars of non-brittle with that of brittle materials under tension.

(After Th. Pöschl, 1930; reproduced from *The Physics of Solids and Fluids*, by permission of Blackie & Son, Ltd.)

most, but not all, of the lengthening is localized near the point where yielding begins, some local point of weakness "always present on account of small differences of structure."

If we consider these diagrams as cross-sections of sheets instead of bars, we have a first approach to a mental picture of what changes of form may be expected in the earth's crust under tension. Experimental studies of the deformation of confined rock materials under compression have shown that for all but the outermost skin of the earth the materials of the crust must behave after the manner of non-brittle materials. We must, correspondingly, look to the forms of deformation in non-brittle materials for our understanding of the mechanical implications of the hypothesis of crustal tension.

[39] Reproduced from P. P. Ewald, Th. Pöschl, and L. Prandtl, *The Physics of Solids and Fluids*, London, 1930, p. 18, Fig. 14.

Turning to recent geological experiments on tension, we note first that beeswax and clay are the typical non-brittle materials that have been used for over a century to reproduce the details of folding exhibited by limestones and sandstones, even by quartzites. It is important that we realize that not only the ductility but also the low strength of these materials is essential in order to render the model true to nature.

All experiments in which natural processes are to be imitated on a small scale can be successful only if the dimensions of all factors involved are reproduced to scale. Since generally the different factors are not in linear relations to each other, an empirical determination of their relative magnitudes in nature and in the model must precede any systematic experimentation aimed at quantitative accuracy as, for instance, in the construction to scale of models in hydraulic laboratories.[40]

Even where no quantitative accuracy can be hoped for, as in the experimental reproduction of the larger structural features of the earth's crust, at least a rough approach to a reduction of all factors to scale must be made. This is the reason why beeswax and a mixture of wax and plaster of Paris have proved useful when rock folds, measuring a few miles from crest to crest in nature, were reproduced in models, measuring a few centimeters from crest to crest, in minutes instead of tens of thousands of years.

Correspondingly, when folded mountain systems measuring hundreds of kilometers in width are to be reproduced on a laboratory table, still weaker materials must be used in order to reduce the strength of the earth's materials to scale. This reasoning led Cloos to use a paste of clay and water for experiments designed to reproduce the larger structural features of the earth's crust. He uses a smooth table top on which rests a thin movable metal sheet covering only a part of the table. A thin layer of the paste is spread out with a trowel in such a way that about half of it overlaps onto the metal sheet. The latter is moved forward or back by means of a suitable mechanism,

[40] See, for instance, the table of relative magnitudes in nature and model in Th. Rehbock, "Das Karlsruher Flussbaulaboratorium und die Aufgabe des Wasserbaulichen Versuchswesens," *De Engenieur*, The Hague, November 19, 1921, No. 47, p. 4.

subjecting the mud either to compression or to tension.[41] In later experiments, the thin sheet of clay paste was spread on a rubber sheet capable of stretching over its whole width.[42] With this simple apparatus Cloos obtained results of greatest interest.[43]

Fig. 33[44] shows the results of a typical experiment in which a thin layer of a half-liquid paste of clay and water, of which only a section

Fig. 33. Model of a furrow produced through crustal expansion. Note fault on left side. (Thin layer of a soft paste of wet clay stretched by means of movable support.) (After H. Cloos, 1929)

is here shown, was subject to tension. The left half rested on the movable plate and was pulled to the left. The similarity with the steel rods in Figs. 31 and 32 is obvious. If this is taken as a model of the earth's crust with the thickness equalling say 60 miles, the furrow measures about 130 miles in width (on front of block) and is over 14 miles deep.[45]

In this case, the tension was localized along the edge of the movable plate. When a half-liquid paste of clay and water is placed on a rubber sheet and then subjected to tension, at first every particle of clay

[41] For a picture showing this laboratory arrangement, see Fig. 1, p. 227, in H. Cloos, "Künstliche Gebirge," published in *Natur und Museum* (Senckenbergische Natur. Ges., Frankfurt a.M.), Heft 5, 1929.

[42] H. Cloos, *op. cit.*, Heft 6, 1930.

[43] "Such experiments have real value only for those who have seen them in action and have carried them out themselves. Only through the experiment arises that vital connection between movement and structure, without which structural geology remains a dead science." H. Cloos, *op. cit.*, 1930, p. 259. (Free translation.)

[44] H. Cloos, *op. cit.*, 1929, Fig. 6, p. 233.

[45] The model does not, of course, reproduce the modifying effect of isostasy, which would greatly reduce the depth of the furrow, so far as sedimentation does not counteract its effect. (See p. 222.) The same remark applies to the model of mountains, Fig. 34.

tends to pull away from every other until actual yielding begins at the point which accidentally proves to be weakest. From that moment on most of the further pulling apart takes place in the immediate vicinity of the point of first yielding, the rest of the clay mass behaving very much as in the examples illustrated above.

The details of fracturing and bending as shown in these models are of great interest and are being studied by Cloos with great skill. We cannot concern ourselves with them here. The illustration given may serve as a first approach to a mental picture of the behavior of the earth's crust under tension.

The hypothetical picture presented on the preceding pages involves, however, a reversal of stresses, which ultimately places the whole crust under compression. Fig. 34[46] shows the behavior of clay paste

Fig. 34. Model of welts produced through crustal shortening. Note direction of thrust planes and arcuate welts surrounding "intermontane spaces." (Thin layer of a soft paste of wet clay thrown into wrinkles by means of movable support; the "intermontane spaces" caused by pieces of harder paste.)
(After H. Cloos, 1929)

under compression. Here the movable plate is pushed to the right causing the thin layer of a half-liquid mixture of water and clay to wrinkle. At first sight this model does not seem to fit reality. In nature, there is nothing to take the place of the solid plate that carries the inert, weak cake of clay forward. The process suggested in the

[46] H. Cloos, *op. cit.*, 1929, Fig. 5, p. 231. The arcuate character of the folds is due to pieces of more coherent clay which form the "intermontane" areas.

hypothesis simply assumes that the subcrustal body of the earth diminishes in size, carrying each particle of the crust downward and crowding it against its neighbors. If the earth's crust consisted of a perfect liquid, this would result merely in a thickening of the crust. Since the crust is not a liquid, it must yield somewhere. If it were perfectly uniform, it would yield uniformly giving rise to innumerable wrinkles. Since it is far from uniform, it will yield sooner at some points than at others. As soon as yielding has begun at these weakest points, the rest of the crust is spared further strain, the shortening of the crust being taken up by the zones of yielding as in the experiment.

The hypothesis here suggested is that the border lines of geosynclines, formed in the geosynclinal phase, represent the chief lines of weakness when the crust is placed under compression in an orogenic cycle. There is no transmission of stress in the sense of vault stresses or of bending beams. Now as before the earth's crust corresponds to the mixture of water and clay of the model.

The field evidence for the contention that the crust actually yields to tangential compression in a "plastic" way will be given in detail in a later chapter. There this part of the hypothetical framework of ideas will be stated formally as an "opinion." The assumed relation of crustal folds to furrows may be formulated as follows:

Opinion 16. Under compression, the crust yields at its weakest points, that is, chiefly along the edges of, or within, the sediment-filled or unfilled furrows, where the crystalline portion of the crust is thinnest. The form of the furrows, therefore, determines the alignment of the crustal folds.

We can form a picture of the crust's behavior from the structures visible at the surface and thus check the hypothesis of an alternating expansion and contraction of the earth's subcrustal body. As far as possible causes of this behavior are concerned, we can do no more at present than guess. A vague suggestion in that direction will be made later in this volume. Here it may suffice to call the attention of those who feel the need of some physical picture for the process to the ideas of others who have suggested alternate expansion and contraction of the crust.

5. Causes Suggested by Others for Subcrustal Expansion and Contraction

Since the writer's first presentation[47] of these views before the Geological Society of America at the Chicago meeting in 1920,[48] when he refused likewise to be led into speculation concerning causes, Joly has published his concept of a cyclical alternation of subcrustal expansion and contraction from the point of view of the thermal condition and assumed thermal history of the earth. The reader is referred to Joly's paper and his later book[49] for a summary of one possible outlook toward an ultimate physical understanding of the mechanism. Joly's views are based, however, on Airy's interpretation of gravity anomalies, that is, he assumes profound "roots" of the mountains and bases his inferences of thermal changes on this conception. In this respect, his reasoning conflicts with the results of this discussion.

An entirely different mechanism for a possible subcrustal expansion was suggested by Tammann in connection with his investigations on melting and crystallization under high pressures. His theoretical results are still being debated. As a suggestion of another way of explaining a cyclic alternation of compressive and tensile stresses in the crust, the reader will find his suggestion interesting.[50]

[47] As far as the writer knows, Rothpletz was the first to suggest alternate contraction and expansion as the mechanism of crustal deformation. He thought that the more exact and detailed the timing of geological events grew the more it became evident that volcanic activity and mountain folding were never contemporaneous. It can be shown that he is probably wrong. Even if he should have been correct, our chronology is at present still so crude that his argument remains without force. See A. Rothpletz, "Über die Möglichkeit den Gegensatz zwischen Contractions- und Expansions-theorie aufzuheben," *Sitz. Ber., Math.-phys. Kl., Kgl. Bayr. Akad. Wiss.*, München, Vol. 32, 1903, pp. 311-25.

[48] "The probable cause of the localization of the major geosynclines," Abstract, *Bull. Geol. Soc. America*, Vol. 32, 1921, p. 75.

[49] J. Joly, "The Movements of the Earth's Surface Crust," *Philos. Mag.*, 6th ser., Vol. 45, 1923, pp. 1167-88; Vol. 46, 1923, pp. 170-5; J. Joly, *The Surface-History of the Earth*, Oxford, 1925.

[50] G. Tammann, "Ueber Aenderungen des Aggregatzustandes bei der Abkühlung eines Weltkörpers," *Verh. d. Permanenten Seismischen Kommission der K. Akad. Wiss.*, St. Petersburg, 1903, Vol. I, Lieferung 2, pp. 321-8.

CHAPTER VI

MARGINAL DEFORMATION

"The value of experience is not in seeing much, but in seeing wisely."
William Osler, in collected *Counsels and Ideals.*

1. Typical Regions

In the preceding chapters, the vague terms "welts" and "furrows" were used to describe the rising and sinking strips of the earth's crust that constitute the mobile belts at any given epoch of geological time. No attention was given to geological structure because the laws so far discussed apply irrespective of structural differences. From these more general laws we turn now to those which apply more specifically to the tectonics of the orogenic belts.

The belts of relatively simple rock-folding come to mind at once as suitable objects on which to begin the inquiry into the meaning of orogenic structures themselves. Some of these in Europe and North America have served for a century as illustrations of rock folding in elementary geological instruction. Others are only now becoming known in detail. In the United States, the folded Appalachians have been made classical by Willis' analysis[1] and important details are accessible in uniform presentation in the folios of the *Geologic Atlas of the United States.* A comprehensive view of the folds of the Ouachita Mountains has only most recently become available through the publication of the geological maps of Arkansas[2] and Oklahoma.[3]

[1] Bailey Willis, "The Mechanics of Appalachian Structure," *U.S. Geol. Survey, Thirteenth Ann. Rept.,* 1891-1892, Part. II, pp. 211-82.

[2] G. C. Branner, *Geologic Map of Arkansas* (1:500,000), Arkansas Geol. Survey, 1929.

[3] H. D. Miser, *Geologic Map of Oklahoma* (1:500,000), United States Geol. Survey, 1926.

For references to the literature on the Ouachita Mountains, see the following recent papers: Sidney Powers, "Age of Folding of the Oklahoma Mountains," *Bull. Geol. Soc. America,* Vol. 39, 1928, pp. 1031-79; H. D. Miser, "Structure of the Ouachita Mountains of Oklahoma and Arkansas," *Oklahoma Geol. Survey, Bull. 50,* 1929; Carey Croneis, "Geology of the Arkansas Paleozoic Area," *Arkansas Geol. Survey, Bull. 3,* 1930; W. A. J. M. van Waterschoot van der Gracht, "Permo-Carboniferous Orogeny in South-Central United States," *Bull. Am. Assoc. Petrol. Geol.,* Vol. 15, 1931, pp. 991-1057.

Similar folds on a scale smaller than that of the Appalachians line the front of the Rocky Mountains in Montana[4] and Alberta.[5]

In the California Coast Ranges, between the prominent rift lines and minor zones of normal faulting, belts of relatively simple folding occur, comparable in many respects to those mentioned above. So long as we think only of the folds within one block bounded by the normal faults, and not of the whole of the Coast Range belt, they belong properly to the group of structures here considered. We shall reserve their discussion for later, however.

In Europe, the Jura Mountains[6] are the classical ground of studies in mountain folding. The Jura Mountains are the best known part of the larger belt of folding that follows the margin of the Alps to the Mediterranean.

Of the numerous zones of simple folding in Europe that are older than the Alpine system, the folds of Paleozoic rocks (with Permian in the synclines) which form the outer zone on the west side of the Ural Mountains[7] seem to be especially similar to those of the Jura Mountains.

[4] See, for instance, the map and sections in Eugene Stebinger's "Oil and Gas Geology of the Birch Creek-Sun River Area, Northwestern Montana," *U.S. Geol. Survey, Bull. 691 E.*

[5] See, e.g., the following geologic maps published by the Canadian Geological Survey: Calgary sheet, Map 204A; Cadomin sheet, Map 208A; Mountain Park sheet, Map 209A. See also the geologic map of Upper Elk and Upper Highwood Rivers, B.C., and Alberta, 1924, to accompany a memoir by J. R. Marshall, "The Geological and Topographical Map of the Moose Mountain Region of the 'Disturbed Belt,' Southern Alberta," which accompanies D. D. Cairnes' Memoir on that region (*Memoir 61,* 1914).

[6] The vast literature on the whole of the Jura Mountains has been treated analytically in a model fashion by E. de Margerie in the "Mémoir pour servir a l'explication de la Carte Géologique détaillée de la France," entitled *Le Jura.* Map II, which accompanies this work, gives a graphic picture of the status of topographic and geological mapping up to 1920. Map I comprises a valuable structure map (in contours) and a hypsometric map. The knowledge concerning the Swiss part (the best known) is summarized admirably in Alb. Heim, *Geologie der Schweiz,* Vol. II, Leipzig, 1919, pp. 443-704.

[7] According to Duparc, as quoted in S. von Bubnoff, *Geologie von Europa,* Band I, Berlin, 1926, p. 86. See *Geological Map of the Ural,* 1 :1,000,000, composed by the Uralian section of the Geological Survey of USSR, Moscow, 1930.

2. Depth of Folding

General statement. Concerning the typical belts of folding and the host of comparable folded zones that flank most larger "welts," the following general statement holds good:

Law 21. Folding of the Jura and Appalachian type is essentially superficial, that is, it involves only an outer fraction of the crust.

That the deformation in some of the most regularly folded regions is probably merely a superficial phenomenon was suggested by E. Suess as early as 1873. It seems to follow from the mere geometry of the cross-sections. In the second volume of Chamberlin and Salisbury's *Geology*, on pages 125-6, the geometrical aspect is tested for its quantitative consequences. If the original width of the folded tract, the amount of shortening and the average amount of uplift are known, the thickness of the folded shell can be computed. Casual computation based on estimated figures showed "that a shell of a very few miles only was involved in the crumplings of the folded mountains."

Computing the depth of folding in Appalachians. In 1905, R. T. Chamberlin undertook to secure accurate data from which the depth of folding might be computed with greater confidence. His paper,[8] published in 1910, constitutes an important contribution to method and theory. Nearly four hundred dips were measured along a line between Tyrone and Harrisburg, Pa., at right angles to the strike of the folds. The structure was plotted to scale and the folds reconstructed on the surface of a resistant sandstone formation.

In the western part of the section, the "thin, but strongly resistant Oriskany sandstone" was used as reference level. At the crest of the nearly symmetrical anticline near Iroquois station, the reference level was shifted to the base of the Catskill sandstone to keep it as much as possible within sight. The whole section was thus restored up to the top of the Pottsville conglomerate. (Fig. 35).[9]

A thin copper wire was placed upon the cross-section and bent so as to follow accurately the line of the reference level. The wire was then straightened out and measured. This gave the original length of the section and the amount of shortening. For the whole section be-

[8] R. T. Chamberlin, "The Appalachian Folds of Central Pennsylvania," *Jour. Geol.*, Vol. 18, 1910, pp. 228-51.

[9] Fig. 6, p. 245, of Chamberlin's paper.

tween Tyrone and Harrisburg, Chamberlin found 81 miles compressed into 66 miles. His discussion of the disturbing factors and the probable limits of error affecting all these determinations may be read in the original.

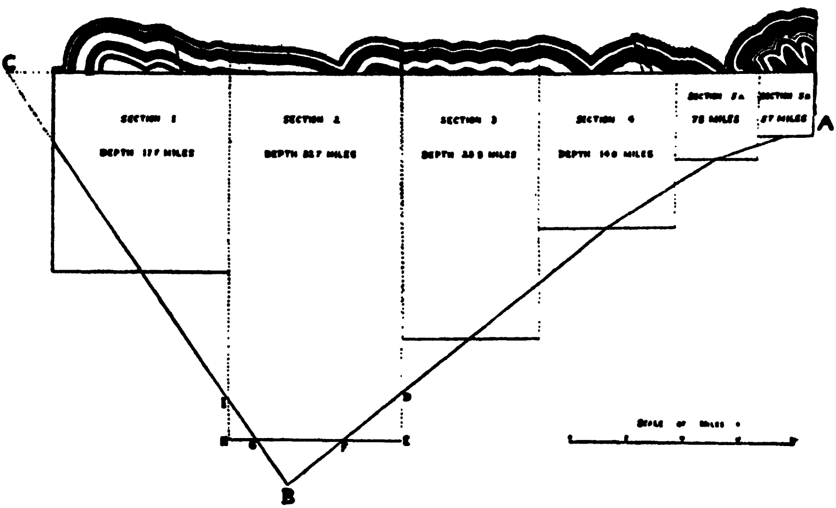


Fig. 35. Cross-section of a portion of the folded Appalachians, from Tyrone to Harrisburg, Pa. Beneath each of the parts into which the section is divided, the depth of folding is indicated according to R. T. Chamberlin's method of computation. (R. T. Chamberlin, 1910)

The average elevation of the tract due to the folding cannot be determined accurately. A reasonable estimate can, however, be made on the following basis. The last sediments laid down before folding seem to have been the upper barren coal measures, that is, sediments obviously laid down not far from sea level. After the folding, a new erosion level, presumably subaerial, was established near sea level, represented today by the remnants of the highest peneplain of the region, the Kittatinny peneplain. The average vertical distance from the original surface of the sediments to the Kittatinny peneplain should roughly be a measure of the uplift due to folding, ruling out that part of the present elevation which is due to Cenozoic crustal movements. Certainly between one and two thousand feet of post-Pottsville strata have been removed by erosion from the folds as seen today. Their exact thickness will never be known. It is probably comparable, roughly, to the thickness of beds that lie between the

Kittatinny peneplain and the railroad level which forms the base line of measurement. The average height of the folds above the railroad give, therefore, as good an estimate of the average uplift due to folding as can be obtained conveniently.

The section was photographed and the prints carefully cut with the railroad level as base line and the top of the Pottsville conglomerate as sky line. The paper sections were weighed and compared with the weight of a section of the same length constructed with a uniform height representing one inch. In this way the average height of the top of the restored Pottsville conglomerate over the section from Tyrone to Harrisburg was found to be 3.01 miles.

From these figures the average thickness of the folded shell may be computed by means of the equation

$$l.\, u = s.\, d$$

in which l equals the present length of the section; u equals the amount of uplift; s equals the amount of shortening the section has suffered; d equals the unknown thickness. The resulting thickness is 13.2 miles.

This is not the outcome of R. T. Chamberlin's paper. Instead of limiting himself to a computation of the average effect over the whole measured distance, Chamberlin divides it into six sections, as shown in his diagram reproduced in Fig. 35. He says, "as the thickness of the wrinkled shell is liable to be variable, it is necessary, in order to ascertain the true significance of the thickness and its variability, to consider separately the several dissimilar parts which make up the section."

To the writer, this mode of procedure seemed questionable. To test it as well as the usefulness of the method as a whole, he turned to Willis' classical experiments.[10] In the plates accompanying Willis' paper photographic reproductions of folds are available for which shortening and average uplift can be obtained by Chamberlin's method and the computed depth of folding can be checked directly by measurement. To test the usefulness of the method as a whole, the writer used two of Willis' figures, Pl. LXXVII *d* and LXXXI *g*. The line representing the surface of one key bed from each of these fig-

[10] Bailey Willis, "The Mechanics of Appalachian Structure," *U.S. Geol. Survey, Thirteenth Ann. Rept.*, 1891-1892, Part II, pp. 211-82.

ures was transferred onto graph paper. The assumption was made that the lowest and least disturbed part of the bed represented its original position. The depth of folding was then computed which in the figures corresponds to the distance from the assumed original level of the key bed to the bottom of the layers used in the experiment.

The depth of folding was obtained with an error of 5.5 per cent in LXXVII *d* and 5.7 per cent in LXXXI *g*, when the little disturbed "foreland" on the left of the folds was omitted from computation. If enlargements had been used, the error would probably have been smaller. Even as it stands, this test proves the general usefulness of this method within the limits of error inevitable in most geological computations.

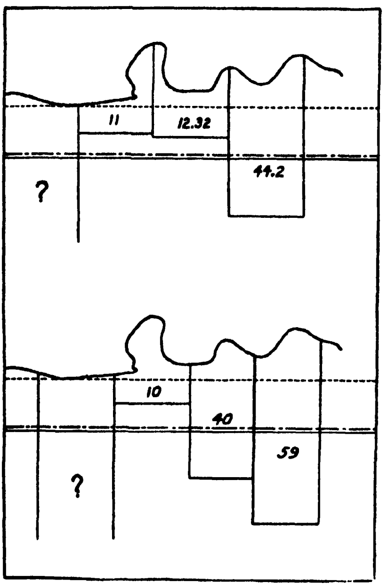


Fig. 36. Cross-section of the folds produced by Bailey Willis in one of his experiments with a compression box. The folds are divided into units comparable to those employed in Fig. 35. Beneath each unit the depth of folding is given as computed by the method employed in Fig. 35. The heavy line marks the bottom of the compression box. The dotted line gives the depth of folding obtained when computed for the whole chain of folds.

Then the writer divided the two cross-sections into four parts comparable to Chamberlin's divisions of his Tyrone-Harrisburg section in their relations to the structural units. The results for one of these sections, Pl. LXXXI *g*, is shown on Fig. 36. When the depth of folding was computed for such small units, it became evident that the writer's doubts were justified. In Fig. 36 the true and computed depths for the section as a whole are indicated by dotted lines. The solid rectangles below each division represent the "depths of folding" computed for the small structural units. A comparison of Fig. 36 with Chamberlin's diagram (Fig. 35) shows that the same relation exists in both between intensity of folding and

supposed depth of folding. The steeper the dips in the section, the shallower the supposed depth of folding. This seems to prove that it is not feasible to subdivide a series of folds into small units and to compute the depth of folding for each separately. When Chamberlin's method is applied to the whole series, on the other hand, valuable results may be obtained for the average depth of folding.

Computing the depth of folding in Jura Mountains. Another test of the usefulness of Chamberlin's method suggested itself. In his student days, the writer received in the field a lasting impression of the extraordinary accuracy with which many parts of the Swiss folded Jura Mountains have been mapped. There are not many regions in the world of which cross-sections are available based on such accurate data and constructed with such scrupulous care. Beautiful series of such cross-sections have been made generally accessible in Heim's *Geologie der Schweiz*, Vol. I, Pls. XXII to XXV. One of the writer's graduate students applied Chamberlin's method to Section 8 on Pl. XXIII (opp. p. 582) of *Die Geologie der Schweiz*. At the northwestern end of this section the folds die out in the nearly level rocks of the Jura plateau. It was assumed that the elevation of the folds of the key bed chosen (top of Dogger) above the average level of the same bed in the plateau gave an approximate measure of the uplift due to folding. Computation by Chamberlin's method gave the depth of deformation as 852 meters.

For half a century, students of the Jura folds have recognized that the dimensions of the folds seen at the surface are such that it is impossible to carry their structure downward through the Lower Triassic and Permian beds into the substructure of the crystalline Paleozoic rocks. Buxtorf[11] added to this geometrical fact the field observation that from the smallest to the widest and highest anticlines not one shows in its center a trace of the calcareous lower Middle Triassic or the red bed series of the Lower Triassic and Permian, not to speak of the pre-Permian crystallines. The cores of the anticlines show no beds older than the Middle Triassic.

The inference seems inevitable that the well bedded rocks above the limestones of the lower Middle Triassic ("Wellenkalkgruppe")

[11] A. Buxtorf, "Geologie des Weissensteintunnels," *Beiträgc z. Geol. Karte d. Schweiz*, N.F., Lief 21, 1907; "Bemerkungen über den Gebirgsbau des nordschweizerischen Kettenjura, im besonderen der Weissensteinkette," *Zeitschr. Deutsch. Geol. Ges.*, Vol. 63, 1911, p. 366.

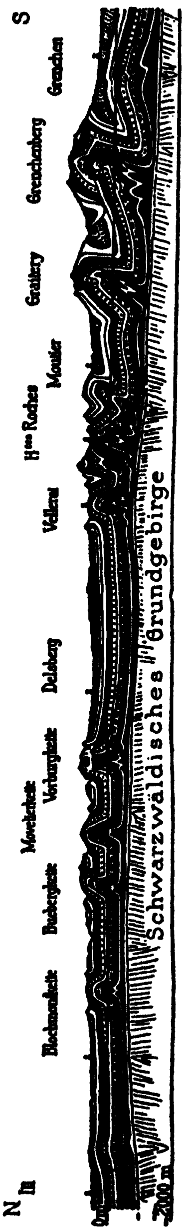


Fig. 37. Cross-section of the folds of the Swiss Jura Mountains. Note that the folding does not extend down to the base of the sedimentary series. The sedimentary mantle is sheared off on top of the basal sandstone which rests on the metamorphic substructure.

(A. Buxtorf, 1908)

have been sheared off the largely thick-bedded, much less yielding, lower sedimentaries. The lowest beds involved in the folding represent the first thick series of yielding shales one encounters going up from the crystalline basement. The presence of rock salt beds in this so-called "Anhydritgruppe" contributes to the mobility of this horizon. Fig. 37, drawn by Buxtorf[12] illustrates the shearing off of the sedimentaries as it is now generally accepted by Swiss geologists. Field observation thus makes it almost certain that only the strata above the "Wellenkalk" were involved in the folding, that is, not more than one thousand meters, according to Heim's sections. This figure agrees as well as may be expected with the figure obtained by Chamberlin's method, viz. 852 meters.

The problem. The considerations that apply to these two classical regions, the Appalachians and the folded Jura Mountains, must hold good in all similar cases. The vast difference in the scale between the two regions gives perspective to our reasoning.[13] In one, the earth's crust lies crumpled to a depth of about half a mile. In the other, perhaps more than ten miles, that is, anywhere from one-sixth to one-third of the earth's crust, are involved in

[12] Reproduced from Fig. 100, p. 602, of Heim's *Geologie der Schweiz*, Vol. I, 1919 (original published in 1908).

[13] A fine map showing the Appalachians and the Jura Mountains side by side, on the same scale, is given by De Margerie, *op. cit.*, Pl. xxx.

the wrinkling which must extend well into the pre-Cambrian basement.

But even Appalachian folds are superficial features of the crust, if our conception of the crust is correct. This raises a fundamental question: In what way is it possible to apply locally a stress to the upper part of the earth's crust in such a way that an outer fraction of it is sliced off and thrown into wrinkles?

3. Marginal Character of Deformation

General statement. The solution to the problem stated in the preceding paragraph lies wrapped up in the adverb "locally." Belts of relatively simple folding do not exist independently. They bear a definite relation to larger structural units. This we may express in the form of a law.

Law 22 a. Each belt of relatively simple folding in sedimentary rocks borders on a region of the earth's crust which in the process of folding assumed the character of a "welt" or continued to rise as such, if formed during an earlier orogenic epoch.

Law 22 b. The intensity of deformation increases toward the edge of the welt and dies out in the opposite direction.

The Jura Mountains, like their southward continuation in the subalpine chains of southeastern France, are obviously an outer fringe of the mighty "welt" of the Alps. The same is true of the folding and thrusting in front of the northern Rocky Mountains and the outer metamorphosed zone of folds on the west side of the Urals.

The "land Appalachia" which furnished again and again coarse clastics to the furrow that now displays the Appalachian folds has played the rôle of a welt throughout the Paleozoic. But the very region from which the greatest thickness of sediments was derived in the later Paleozoic, the Piedmont around Baltimore and Philadelphia, does not suggest in its present-day topography the deformation of the crust that made possible the removal of such quantities of rock waste. Where a similar condition prevails along the whole length of a folded belt, the validity of law *22* is by no means obvious.

The marginal character of the Ouachita folds. In the case of the Ouachita Mountains, the region from which the active thrust must have come lies buried beneath the Cretaceous cover. H. D. Miser[14]

[14] H. D. Miser, "Llanoria, the Paleozoic Land Area in Louisiana and Eastern Texas," *Am. Jour. Sci.*, 5th ser., Vol. 2, 1921, pp. 61-89.

has summed up the information that proves the presence of an active source of sediment south of the Ouachita folds. By analogy to "Appalachia" he has called this old land "Llanoria."[15] This land mass furnished most of the 20,000 to 25,000 feet of sediments that now constitute the folded belt north of it. Fully 90 per cent of these rocks are clastic. In general, the thickness and coarseness of the sediments decreases rapidly as one moves north away from the folded area. Thus, for instance, the Pennsylvanian Atoka formation, 6,000 to 7,800 feet thick in the folded portion of the Arkansas Valley and in the Ouachita Mountains, dwindles to a minimum of 200 to 400 feet in the Winslow formation of the unfolded regions to the north. Summarizing the evidence concerning Llanoria, Miser says:[16] "At times, as during the Devonian period, it had very little relief, but at other times, as during the Ordovician and Silurian periods and the Mississippian and Pennsylvanian epochs, it was mountainous. . . . The increase in the intensity of the folding of the rocks in the Ouachita Mountains and Arkansas Valley toward the south suggests that the deformation of the basement rock of the Gulf Plain south of these regions was still greater." The inference contained in the last sentence implies that the northern part of the "land Llanoria" was a zone of active orogenesis, a "welt," and not merely the edge of a "positive element," or as we would call it, a "swell." This is probably what Ulrich meant when he wrote:[17] "To the south of the original Ouachita basin lay an older foreland that, although included in, is not strictly the same as the 'Llano' of Schuchert or 'Llanoria' of Dumble, Powers, and more recently Miser."

Folding within a frame of preexisting relief. In the case of smaller folds in larger structural basins, the marginal character of the deformation has long been recognized. One of the best known cases is that of the folding in the Bighorn Basin, Wyoming. Here folds form a belt fifteen to twenty-five miles wide around the border of the basin. On the west side they are partly concealed by the thick cover of approximately horizontal tuffs and lavas beneath which they

[15] In place of the name "Llano" first employed by Bailey Willis, "A Theory of Continental Structure Applied to North America," *Bull. Geol. Soc. America,* Vol. 18, 1907, pp. 394-5.

[16] *op. cit.*, p. 88.

[17] E. O. Ulrich, "Fossiliferous Boulders in the Ouachita 'Caney' Shale and the Age of the Shale Containing Them," *Oklahoma Geol. Survey, Bull. 45,* 1927, p. 26.

may extend much farther west than actual outcrops indicate. In the southern part alone, Hewett and Lupton[18] described fifty domes and anticlines. The largest folds are those which lie near the edge of the basin. These involve pre-Tertiary rocks at the surface. The folds that lie farther away from the edge are limited to Wasatch and younger Tertiary rocks. The innermost folds are the smallest and least conspicuous. With reference to the depth of folding Hewett and Lupton wrote:[19]

". . . There is little doubt that some of the larger anticlines . . . involve pre-Cambrian rocks. Others . . . are so narrow and have limbs so steep that although they may go down to the Chugwater (Triassic) they do not persist to the Big Horn (Ordovician) and Deadwood (Cambrian) formations. Other small folds . . . may not persist below the Madison (Mississippian) limestone."

A fine European illustration is seen in the folds of the Transylvanian basin of which Mrazec and Jekelius have published recently an instructive tectonic sketch map.[20] The map shows the strike of the Neogene rocks of the basin swinging around the edge of the oval basin. An outer zone displays strong folding which dies off rapidly away from the edge toward the center of the basin where the beds lie practically level with scattered rounded domes.

That such superficial folding in basins is rather generally dependent on the margins has long been recognized. Suess speaks of "Rahmenfaltung" in central Europe, of folding within a frame of preexisting relief.[21] Stille[22] has worked out this relation in detail for the region of the "Niederdeutsche Becken." A line drawn from the northeast corner of the "Rheinische Schiefergebirge" through the Sölling and Harz Mountains to the "Flechtinger Höhenzug"

[18] D. F. Hewett and C. T. Lupton, "Anticlines in the Southern Part of the Big Horn Basin, Wyoming," *U.S. Geol. Survey, Bull. 656,* 1917. See also the map of the "Oil and Gas Fields of the State of Wyoming," prepared by G. B. Richardson and K. C. Heald, on the scale 1:500,000, published by the U.S. Geological Survey, 1921.

[19] *op. cit.,* p. 34.

[20] L. Mrazec and E. Jekelius, "Esquisse tectonique du bassin Transylvain" (1:1,500,000), *Association pour l'avancement de la géologie des Carpathes, Section Roumaine, 2eme réunion, September 1927.* Published by the Institute Geologic al Romaniei. Pls. 2 and 3.

[21] E. Suess, *The Face of the Earth* (Sollas Translation), Vol. IV, p. 295.

[22] H. Stille, "Die Mitteldeutsche Rahmenfaltung," *3. Ber. Niedersächs. Geol. Ver.,* Hannover, 1910, pp. 141-69.

separates the north German basin from the central German swell. The basin received marine sediments well into the Miocene, while in the whole time from the Jurassic to the Miocene the sea transgressed onto the central German swell only twice, in the Upper Cretaceous and in the Middle Oligocene. Beyond the northern edge of the central German swell a number of "welts" have projected northward into the north German basin since pre-Jurassic times, such as the Harz Mountains, Thüringer Wald, Flechtinger Höhenzug, and the large mass of the Rheinische Schiefergebirge. These tectonic prongs consist of the peneplained structures developed during the late Paleozoic epochs of folding, covered more or less by Mesozoic and Cenozoic formations. They are bounded in places by faults and thrusts, as on the north side of the Harz and along portions of the Thüringer Wald.

Locally, flexures take the place of faults, as at points along the sides of the Thüringer Wald. Where there have been no relatively recent movements, the post-Variscan sediments overlap undisturbed onto the peneplained older rocks.

These prongs have the character of welts. Within the basins which they enclose, the Mesozoic and Cenozoic sediments are thrown into folds. On the basis of most careful mapping and intensive study, Stille has formulated the following generalizations[28] which may well be found ultimately to have the character of laws for folding in basins surrounded by welts:

(a) The folding is the stronger, the deeper the strata affected by it had been depressed, that is, the greater the amplitude from the welt to the furrow had become at the time of folding at any given point.

(b) The folds are the more elongated and the more nearly parallel to the edges of the bordering welts, the closer they lie to the edges.

4. The Asymmetry of Marginal Deformation

From the foregoing examples it becomes evident that law 22 extends to all belts of relatively simple folding, no matter how large, the interpretation which is generally accepted for marginal folds in smaller basins only. One characteristic of all such "marginal belts of folding," as we may call them, deserves special emphasis. It is their

[28] H. Stille, *op. cit.*, p. 162.

asymmetry. The folding[24] dies out in one direction and increases steadily in the other, up to the edge of the "welt."

Geologists frequently speak of such asymmetry as the result of a "one-sided pressure." This expression is incompatible with the terminology of mechanics. It sounds like something contrary to Newton's third law of motion. What is meant, of course, is that the asymmetry is the result of the action of an unbalanced pressure. An unbalanced force produces acceleration. The superficial marginal folding is clearly the result of motion induced by unbalanced forces which arise in the course of the larger crustal deformation which creates the welts and furrows. The welts and furrows thus appear as the active parts, while the marginal folding may be called passive.

Opinion 17. Marginal folds are the result of unbalanced pressures arising in the formation of welts and furrows, compared with which they are secondary and more or less accidental features.

[24] The word "folding" has been used throughout this discussion to include the type of thrust faulting commonly associated with folding.

CHAPTER VII

DEFORMATION WITHIN THE WELTS

"Äusseres Tun verrät inneres Sein."
Jacob Wassermann, in *Laudin und die Seinen.*

1. THE SOUTHERN ROCKY MOUNTAINS

If opinion 16 is justified, the mechanism of orogenesis is primarily that involved in the rise of welts. According to the opinions expressed earlier in these pages, the welts represent zones along which the crust as a whole has yielded to tangential pressure. We must now ask ourselves if the structure about and within a welt tells something of the manner of yielding.

Once again we turn to the Colorado Rocky Mountains for an illustration. The crystalline axis of the Front Range, flanked on both sides by foothills of sedimentary rocks, comes to mind at once as an apt example of a "welt." The question is: What is the structural relation of the crystalline core to the marginal belts? Even in this most accessible of the western ranges, we find accurate, detailed structural observations surprisingly scant. Few of the speculative papers in which the mechanism of the rise of the southern Rocky Mountains is discussed are concerned with the observable details of structure which are after all critical.

En échelon folds of eastern edge. The eastern edge of the Front Range has been mapped on a reasonably large scale for most of the length.[1] The normal aspect of the foothills is that of sedimentary formations dipping away from the crystalline core at relatively gentle

[1] From north to south: N. H. Darton, E. Blackwelder, C. E. Siebenthal, "Laramie-Sherman Folio, No. 173," *U.S. Geol. Survey,* 1910 (1:125,000); Junius Henderson, Jas. Underhill, R. D. Crawford, "Geologic Map of the Foothills of North Central Colorado," map in *First Report, 1908, Colorado Geol. Survey,* published in 1909 (1:196,200); N. M. Fenneman, "Geologic Map of the Vicinity of Boulder, Colorado," map in *U.S. Geol. Survey, Bull. 265,* 1905 (1:63,360); G. H. Eldridge, "Areal Geology of the Denver Basin, Colorado," map in *U.S. Geol. Survey, Monograph 27,* 1896 (1:125,000); G. B. Richardson, "Castle Rock Folio, No. 198," *U.S. Geol. Survey,* 1915 (1:125,000); George I. Finlay, "Colorado Springs Folio, No. 203," *U.S. Geol. Survey,* 1916 (1:125,000 and part 1:48,000); Whitman Cross, "Pike's Peak Folio, No. 7," *U.S. Geol. Survey,* 1894 (1:125,000).

angles, rarely exceeding 45°. This leaves the impression, at first glance, of a simple, broad arch which might be thought of as having risen by an essentially vertical movement such as figures so largely in writings on "isostatic" deformation. But merely an inspection of the *Geologic Map of Colorado*[2] on the scale 1:500,000 shows that such a simple conception cannot do justice to the structural detail. In the northern part, between Fort Collins and Boulder, the edge of the crystalline core is drawn out into a series of prongs which project beyond it *en échelon* in a south-southeast direction. South toward Boulder and to beyond Golden the outcrop of the foothill formations narrows conspicuously. Still farther south, the banded outcrops of the sedimentary formations at several places abut abruptly against the crystallines. The most conspicuous case is seen west of Colorado Springs where the Ute Pass fault cuts off the sediments south of the Garden of the Gods.

In 1917, Ziegler[3] showed that the *en échelon* folds of the northern region are asymmetrical, with gentle dips on the northeast and steep, even reversed dips on the southwest side. Furthermore, every fold *en échelon* studied by him in the northern part of the Front Range showed a thrust fault on the west limb of the anticline.

Recent work by members of the U.S. Geological Survey has demonstrated that many, if not all, of the *en échelon* folds are continued within the crystalline mass as nearly vertical zones of crushing and mylonitization.[4] Here then we see the crystalline core of the welt rise near the edge in slices that are forced upward differentially, overriding one another more or less.

Thrust faulting on eastern edge. In the zone between Boulder and Golden, the outcrops of the formations do not only narrow, but as the more detailed maps show, some of the outcrops are suppressed completely. Ziegler[5] has corrected the earlier interpretations of the structural relations originally given by Eldridge and adopted by Fenneman. He has shown that here the front of the range, rising more abruptly, has bulged outward, locally overriding the sediments

[2] Prepared by R. D. George, 1913.

[3] Victor Ziegler, "Foothills Structure in Northern Colorado," *Colorado School of Mines Quarterly*, Vol. 12, 1917, No. 2.

[4] T. S. Lovering, "Preliminary Map Showing the Relations of Ore Deposits to Geologic Structure in Boulder County, Colo." *Proc. Colorado Sci. Soc.*, Vol. 13, 1932, pp. 77-88.

[5] *op. cit.*, pp. 12-29.

of the foothill zone along thrust planes dipping steeply westward. Bloesch[6] has studied details of the vicinity of Boulder without knowing of Ziegler's findings. His sections are here reproduced[7] (Fig. 38).

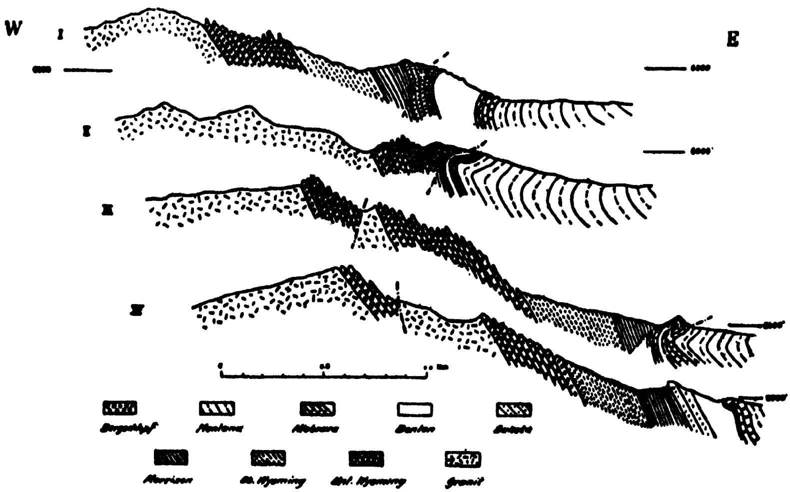


Fig. 38. Structure sections through the edge of the Front Range near Boulder, Colo., showing local overthrusting.

I = South of Two Mile Canyon. III = Pole Canyon.
II = South of Boulder Creek. IV = Bear Canyon.

(E. Bloesch, 1919)

Here again the local bulging out of the rising mountain border is evident.

The Ute Pass fault is the most conspicuous feature of the eastern edge of the Front Range. It forms the southwest border of a synclinal axis that extends from Manitou across Ute Pass to the sedimentary basin of Manitou Park.[8]

The fault itself extends far south-southeast of Manitou, where it forms the edge of the mountains for a distance of over twelve miles, ending abruptly north of Little Fountain Creek. For a better under-

[6] E. Bloesch, "Zur Tektonik der Front Range in Colorado," in *"Heim-Festschrift" der Vierteljahrschrift d. Naturf. Ges. Zürich,* Vol. 64, 1919, pp. 219-45.

[7] *op. cit.*, p. 227. See also V. Ziegler, *op. cit.*, Fig. 4, p. 22, and Figs. 6 and 7, p. 23.

[8] This synclinal belt separates the south-southeast trending crystalline axis to the north of it, the Rampart Range, as the largest of the *en échelon* prongs of the Front Range proper. Cf. *Geologic Map of Colorado.*

standing of the following comments, the maps in Colorado Springs quadrangle should be consulted.

In the text of the Folio, Finlay considers the Ute Pass fault as essentially a normal fault which "dips steeply to the southeast" (p. 11). Unfortunately, the critical word "southeast" is obviously a slip of the pen, since the fault strikes southeastward. The few details of structure along the fault mentioned in the text are largely indefinite. Throughout the text, Finlay minimizes the importance of features not compatible with mere vertical block movement. "A small anticline in the sandstone of the Fountain formation" seen "at one place" is ascribed to the "forward thrust of the granite mass, possibly after the block was upthrown" (p. 11). This same explanation is suggested for the "apparent overthrust relation just south of the Garden of the Gods," where an overthrust displays a fault plane "dipping westward at an angle of about 50°." Here the Pennsylvanian Fountain formation rests on the Cretaceous Graneros shale. Nothing is said about the structural evidence in the underlying beds. Instead of an accurate representation of the conditions at this rather important point three "ideal sections" are shown to illustrate how "compression and forward movement of the granite mass after it was uplifted and faulted by normal displacement" could tilt "the fault plane, formerly vertical." In this diagram the fault is seen to be tilted but little from the vertical, the most inclined part dipping 65°, not 50°, as observed in the field. It is obvious that observations pointing toward distinct overthrusting appeared to Finlay rather negligible exceptions to the preconceived idea of a dominantly vertical movement *en bloc*.

Yet, that overthrusting is by no means a negligible feature along the Ute Pass fault can be seen directly from Finlay's map. At the south end, along the north fork of Little Fountain Creek, the contact between the granite and the Fountain formation is mapped as our Fig. 39 shows (enlarged). All along the "embayment" of the Fountain outcrop north of the creek the contact is seen dipping rather gently inward, beneath the granite. This is a typical picture of the dissected edge of an overthrust mass. Bloesch[9] found the actual contact exposed at one point and determined the dip of the thrust plane as about 25° westward. The sediments dip beneath the granite

[9] *op. cit.*, p. 239.

at an angle but little steeper than that of the thrust plane. East of the contact, the beds dip westward at steeper angles. The Dakota sandstone dips toward the mountains at an angle of 80° and the regular eastward dip is not observed until one reaches the Niobrara limestone, according to Bloesch.

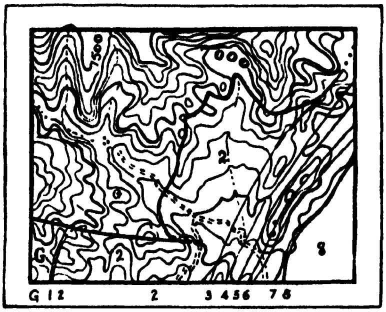


Fig. 39. A small area shown on "Areal Geology" map in *Colorado Springs Folio* (No. 203) enlarged to show the nature of the contact of pre-Cambrian granite and Pennsylvanian Fountain formation, ten miles south of Colorado Springs, Colo.

Normal stratigraphic sequence: *G* = granite (pre-Camb.); *1* = Manitou l.s. (Ordov.); *2* = Fountain form. (Penn.); *3* = Lyons and Lykins form. (Penn.-Perm.); *4* = Morrison form. (L. Cret.); *5* = Purgatoire form. (L. Cret.); *6* = Dakota ss.; *7* = Benton sh.; *8* = Niobrara l.s.

The two faults interpreted in the folio as normal faults seem to be the marginal traces of the thrust sheet of granite of which the rest of the contact represents the dissected front.

Similar relations are reported by Bloesch two to three miles farther north in the upper Limekiln Valley. Here all the beds from the Niobrara limestone downward dip 40° to 60° westward beneath the granite. The contact itself is not exposed, however.

Following the Ute Pass fault northward, Bloesch[10] found the Cretaceous beds along the fault, in the next four to five miles, dipping west in inverted position at angles around 45°. The "sandstone dike" exposed between South and North Cheyenne Creeks dips 60° westward. Near the mouth of Bear Creek Canyon, along the railroad, the Cretaceous beds are seen to dip 45° to 55° westward.

About half way between Bear Creek and Manitou, Bloesch observed the contact of the granite with the underlying Fountain conglomerate. At one point, south of Sutherland Creek, the contact is a thrust plane dipping 60° westward beneath the granite. At the other, about half a mile north of Sutherland Creek, the thrust plane dips 40° westward. In both cases, the underlying Fountain beds are overturned and dip 50° or more westward. At the east entrance of

[10] *op. cit.*, pp. 237-8.

the lower railroad tunnel south of Manitou, the granite is seen overthrust onto the beds of the Fountain conglomerate which dip 40° westward.

Beyond Manitou, toward Ute Pass, the only evidence of the thrust is seen in the minor disturbances in the Sawatch sandstone. One of these is here shown in Fig. 40, reproduced from Crosby's paper.[11] The scale of Crosby's figure is not given, but it is evident from his statement that the white lower portion of the Cambrian sandstone is 10 to 15 feet thick and its total thickness measures 40 to 50 feet.

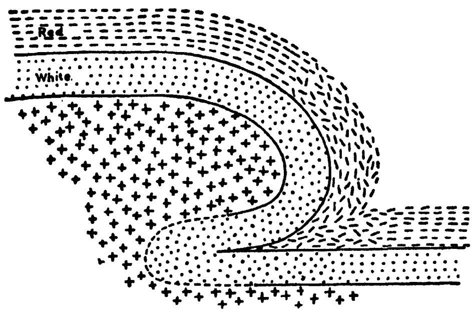


Fig. 40. Detail of the contact of the basal Cambrian beds and the Archean granite on the east side of Ute Pass, northwest of Colorado Springs, Colo. Note the obliteration of the bedding of the sandstone along the vertex of the anticline.
(The white sandstone is 10 to 15 feet thick.)
(W. O. Crosby, 1899)

This fold on the east side of Fountain Creek, north of Manitou, is here reproduced because it shows strikingly a property of the crystalline rocks of the core which is not generally recognized, that of "plastic" yielding. We take sharp folds of this type for granted when they are seen in sediments. But we are not all ready to think of the unstratified, crystalline basement as capable of yielding in similar fashion.

Yet it is just this which the actual contact of the sedimentary beds and the crystalline basement seems to show all along the Ute Pass fault. The crystalline core was obviously not faulted upward as a rigid block and then perhaps shoved over slightly to one side, but everywhere it appears to have bulged outward, "swelled over," as it were, toward the east where the fault trends north-northwest, toward the south when it runs southwestward. The core as it rose was not rigid, but distinctly "plastic" and capable of yielding differentially from point to point. Thus the Ute Pass fault appears as the counter-

[11] W. O. Crosby, "Archean-Cambrian Contact near Manitou, Colorado," *Bull. Geol. Soc. America*, Vol. 10, 1899, Fig. 5, p. 146.

part of the thrust faults in the *en échelon* folds of the northern part of the Front Range, which tell the same story.[12]

Thrust faulting on western edge. On the west side of the Front Range, information is as yet even more inadequate. Recently, T. S. Lovering[13] has "found a thrust fault nearly 60 miles long, extending northwest from Tiger, a small settlement 2½ miles northeast of Breckenridge to a point about 8 miles north of Kremmling. It crops out conspicuously for 25 miles along the western slope of the Williams Range, and the name 'Williams Thrust-fault' is therefore proposed for it. The fault dips eastward or northeastward at an angle of 20° to 30°. Local doming has produced a window in the upper block east of Keystone and exposes the Cretaceous shales capped by pre-Cambrian gneisses to a point 4½ miles east of the main outcrop of the fault. . . . South of Tiger, the fault passes into an overturned fold. Near Kremmling the pre-Cambrian cover has been eroded in many places, leaving many isolated buttes of Cretaceous shale capped by gneisses and schists." The center of the outcrop of this thrust fault lies about forty-five miles west of Golden.

Résumé. For the purposes of this discussion, this striking single observation on the west side of the Front Range suffices. We see the crystalline core of the Front Range forced up and moving differentially in units trending north-northwest-south-southeast. This divergence between the strike of differential units within the core and the axis of the welt is repeated in similar fashion, for instance, in the Bighorn Mountains and probably in other units of the Rocky Mountains. In the Front Range, the structural dominance of the north-northwesterly direction throughout the crystalline core is shown even by the drainage map. We are concerned, not with such detail, but with the evidence of differential upward movement of slices of the crystalline core. These give rise on the edges, at one place, to *en échelon* folds broken by thrust planes and at others to more extensive overlapping of the crystalline mass onto the sedimentary mantle in the form of recumbent folds and extensive thrust sheets carried

[12] Compare also the intricate thrust-faulting which was mapped recently by W. S. Burbank and E. N. Goddard on the east side of the Sangre de Cristo Mountains near Huerfano Park, Colo. Map and cross-sections were exhibited at the Tulsa meeting of the Geol. Soc. America, 1931.

[13] T. S. Lovering, "Williams Thrust-fault," abstract in *Bull. Geol. Soc. America*, Vol. 39, 1928, p. 173.

outward from the margin on both sides.

2. The Bighorn Mountains

The Bighorn Mountains offer another illustration of the structural details along the margin of a moderately compressed welt. Fig. 41 reproduces Darton's diagram of the Bighorn uplift represented by contours drawn at the base of the Madison limestone.[14] This contour map should be used side by side with the geological map in Darton's *Geology of the Bighorn Mountains.*

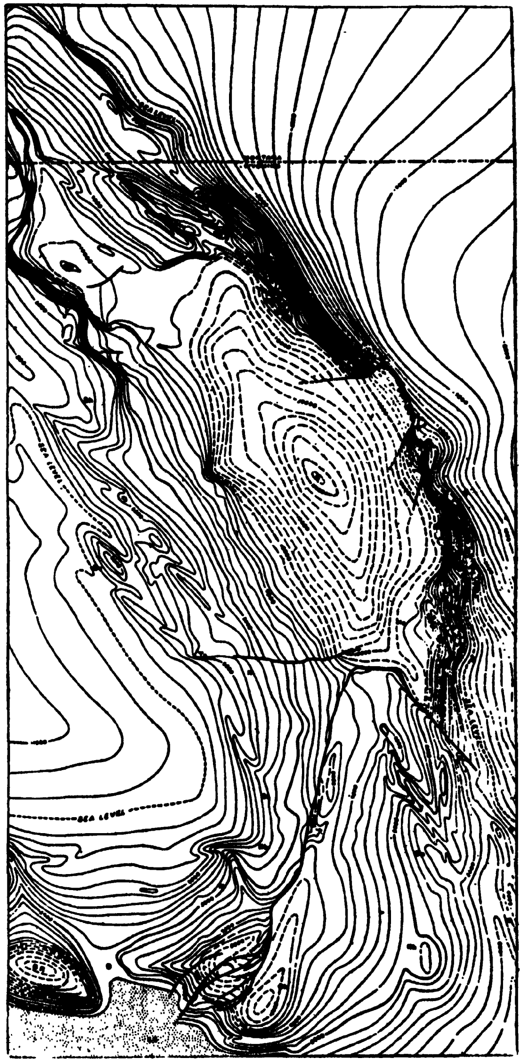


Fig. 41. Tectonic sketch map showing the structure of the Bighorn Mountains of Wyoming by contours drawn at the base of the Madison limestone.
Dashed lines = areas from which all sedimentary rocks have been removed by erosion; heavy lines = faults; dotted pattern = area covered by Tertiary deposits. Contour interval = 500 feet with sea level as datum. The width of this map represents approximately seventy miles.
(N. H. Darton, 1906)

[14] *Cloud Peak-Fort McKinney Folio, No. 142,* 1906, Fig. 5, p. 13; also in "Geology of the Bighorn Mountains," *U.S. Geol. Survey, Prof. Paper 51,* 1906, Pl. XXXVII, opp. p. 92.

Here the welt is asymmetrical in cross-section. Gentle dips prevail on the west side, steep dips in the east.

Almost exactly in the center of the gentle arc formed by the main part of the crystalline axis, along the east-west line separating Sheridan and Johnson counties, the granite cuts across the foothill zone in what appears on the map as a broad prong jutting over two miles eastward beyond the normal edge of the crystallines. Six miles south of the southern border of this "prong," the "granite" projects in a small triangular area which cuts off the foothills, and a little farther south in a second broader lobe. On Darton's map and in the sections these prong-like lobes are shown bounded by normal faults. But the map pattern is unmistakably that of local thrust faults. In July 1931, the writer visited the east front of the Bighorn Mountains along the north fork of Shell Creek, near the northern edge of Fort McKinney quadrangle in Folio 142, in company of Drs. W. T. Thom and R. T. Chamberlin. Here the large fault, shown on the geologic map, was found to be a typical low-angle thrust fault. Nearly vertical Ordovician Bighorn limestone and the underlying Cambrian series are seen thrust onto Mississippian Madison limestone which dips west-

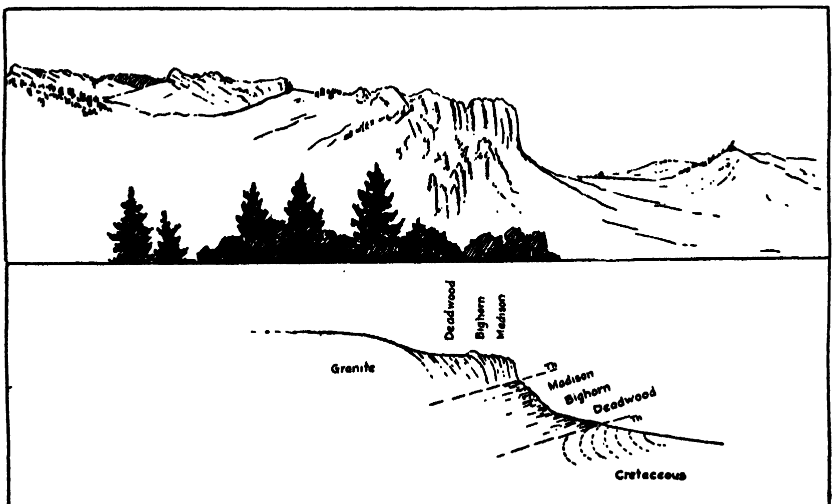


Fig. 42. View and diagrammatic cross-section showing the east front of the Bighorn Mountains along the North Fork of Shell Creek (west of the northern end of DeSmet Lake, Fort McKinney quadrangle, Wyo.).

(Field sketch by the writer, 1931; redrawn by Professor Daniel Cook)

ward, that is, beneath the thrust fault, at low angles. (See Fig. 42.) There can be no doubt, then, that here, and almost certainly also at the other points farther south mentioned above, the east front of the Bighorn Mountains was thrust outward onto the foreland along true thrust faults.

In the northern part of the Bighorn Mountains, the main outcrop of the crystalline axis terminates rather abruptly along an east-northeast line. In its place another axis appears near the western edge of the mountains, offset *en échelon* with reference to the main axis. Here the foothills are turned up steeply on the west side while gentle slopes descend toward the east. On the west side, near the southern end of this western axis, Darton observed a thrust fault along which granite has been pushed up over the middle beds of the Madison limestone which corresponds to a throw of about 1,500 feet. The thrust plane dips about 50° into the granite.[15] The fault is about two miles long, "dying out rapidly in each direction." Similar overthrusts occur along the same mountain front to the northwest. Locally, even the mountain front itself is overthrust on the younger rocks of the foothills as, for instance, where the Dayton-Kane automobile road across the Bighorn Mountains descends abruptly on the west side. Here, the Paleozoic and Mesozoic formations are overturned, dipping eastward, and are overthrust, so that at the foot of the mountain the Jurassic Sundance formation rests on the dark Thermopolis shale of Upper Cretaceous age. (Fig. 43.)

Here, then, we have again clear evidence of differential movements within the crystalline core. Locally, the core has been urged forward, outward.

3. THE HARZ MOUNTAINS

A widely known European example of a simple asymmetrical welt is that of the Harz Mountains.[16] (Fig. 44.)[17] Here the core of the welt consists of intensely folded Paleozoic formations with local

[15] *op. cit.*, p. 98, Fig. 12.

[16] K. A. Lossen, *Geognostische Uebersichtskarte des Harzgebirges*, 1:100,000, Berlin, 1882; Fr. Dahlgrün, O. H. Erdmannsdörfer, und W. Schriel, "Geologischer Führer durch den Harz," Berlin, 1925. (*Gebr. Borntraeger, Sammlung geologischer Führer, Nos. 29 and 30*); *Geognostische Karte von Preussen und benachbarten Bundesstaaten*, 1:25,000, Blätter "Harzburg" u. "Goslar."

[17] Reproduced from E. Suess-DeMargerie, *La Face de la Terre*, Vol. II, Fig. 29, p. 161.

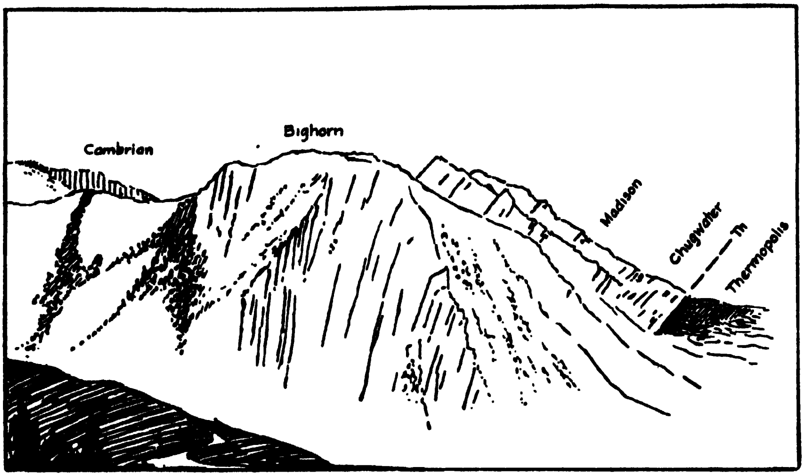


Fig. 43. View showing west front of Bighorn Mountains on Highway 65, east of Kane, Wyo., looking north.
(Field sketch by the writer, 1931; redrawn by Professor Daniel Cook)

intrusives. These trend northeastward, while the axis of the welt strikes west-northwestwards. The core is mantled unconformably by Permian and Mesozoic formations. These slope gently away from the core on the southwest side. On the northeast side, on the other hand, they are turned up abruptly, forming a belt of foothills, entirely comparable to that bordering the Bighorn Mountains. These two welts are quite comparable also as to dimensions. The outcrop of the crystalline core in the Bighorn Mountains proper, with the steep side facing eastward, is about 68 miles long; the core of the Harz Mountains measures about 60 miles in length. Both cores are about one-third as wide as they are long.

The northeast side of the Harz Mountains is quite straight and bordered by rather steeply dipping, even vertical foothills. Between Goslar and Ilsenburg, the Jurassic and Cretaceous beds of the foothills are overturned, dipping under the overriding Paleozoic rocks of the core. There can be no doubt that this "swelling over" of the core represents a local differential movement exactly like that shown in our American examples.

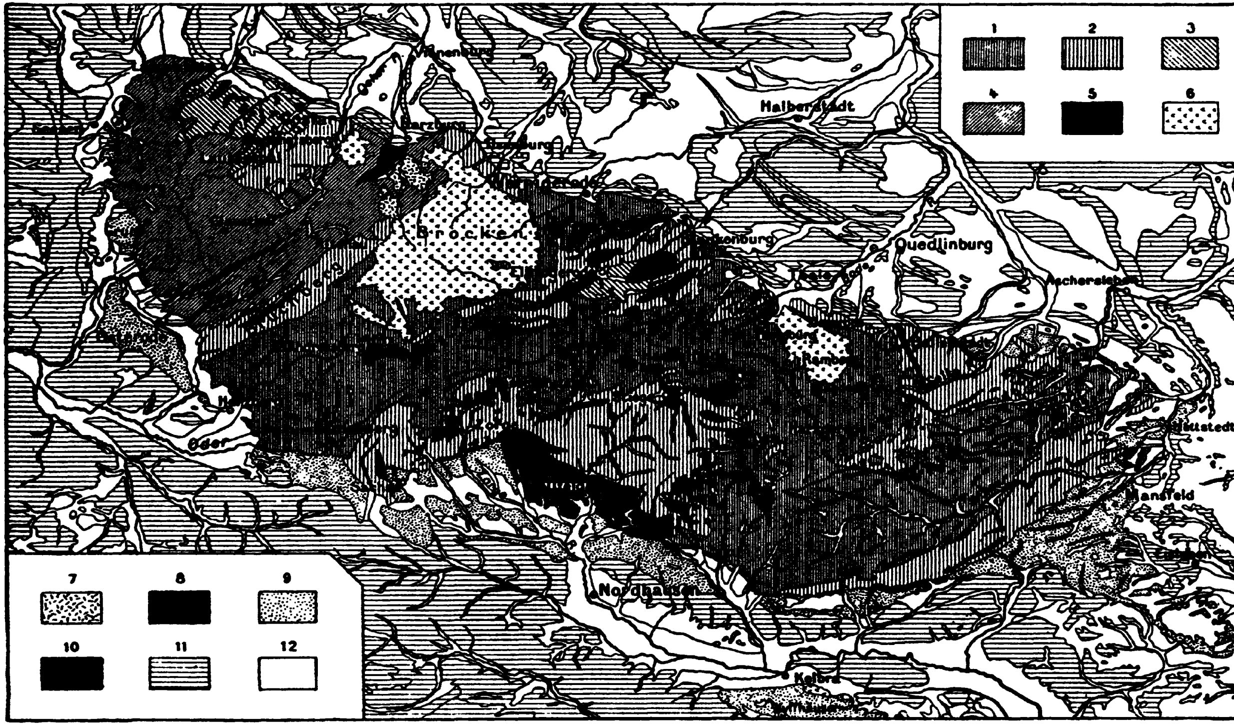


Fig. 44. Geologic map of the Harz Mountains, Germany. Scale 1 : 600,000.
1 = Pre-Devonian ("Hercynian"); *2* = Lower Devonian; *3* = Middle and Upper Devonian; *4* = Lower Carboniferous; *5* = interstratified diabases; *6* = granite; *7* = gabbro; *8* = Upper Carboniferous; *9* = Permian; *10* = porphyries, melaphyres, etc.; *11* = Mesozoic and Tertiary rocks of the surrounding lowland; *12* = alluvium and loess.

The asymmetry of the uplift is shown by the mantle of transgressive Permian sediments (No. 9, stippled) and eruptives (No. 10) which fringes the gently ascending southwest side of the uplift and swings around to the north side at the eastern end. It is missing along the whole western portion of the steeply upturned north side. Here, especially in the vicinity of Harzburg and Ilsenburg, the older rocks of the uplift are overthrust on the belt of foothills.

Note especially the contrast between the strike of the Paleozoic folds of the core and the long axis of the uplift.

(After Lossen and Lepsius, from E. Suess-DeMargerie, *La Face de la Terre*; reproduced by permission of Librairie Armand Colin.)

4. The Crystalline Appalachians

Western edge of Blue Ridge welt. We now turn to welts that have undergone greater deformation. Let us first examine a part of the western front of the crystalline Appalachians. The *Geologic Map of Virginia*, issued in 1928,[18] offers a convenient basis for our discussion. For our purposes, an especially useful map on a larger scale is the "Geologic Map of a Portion of the West Foot of the Blue Ridge, Virginia," published in 1919 by the Virginia Survey[19] on the scale 1:125,000. This scale is the same as that of the Colorado Springs Folio and others of the eastern edge of the Front Range, and makes possible direct comparisons. In Fig. 45 a part of the latter map is reproduced on a smaller scale. But the reader should consult the original, if possible, while reading this discussion.

Our map sketch, Fig. 45, like the original, shows only the Cambrian part of the foothills and the pre-Cambrian greenstones and granitic rocks.

As along the Rocky Mountain front, the outcrops of the sedimentary formations along the west front of the Blue Ridge are arranged in parallel bands. This indicates in a generalized way a monoclinal dip away from the crystalline core. In detail, however, minor folding introduces variable dips and changing width of outcrop. Yet, for miles at a stretch, the fairly simple monoclinal relation prevails, as for instance, northeast of James River to near the Augusta County line, a distance of nearly twenty miles.

At three points along the seventy-mile front shown in our map sketch, the crystalline core is seen to overlap the foothill zone. In the vicinity of the thrust mass, the Cambrian beds of the foothills stand vertical or are "even overturned so as to dip steeply toward the southeast in places." South of Luray, the pre-Cambrian granite is thrust "across the ends of all the siliceous rocks and onto the limestone, a horizontal distance of over four miles."[20]

The similarity with the thrust faults along the Front Range near Colorado Springs is evident. Here again we have great differences

[18] *Geologic Map of Virginia*, 1:500,000, Virginia Geol. Survey, 1928.

[19] In G. W. Stose, H. D. Miser, F. J. Katz, and D. F. Hewett, "Manganese Deposits of the West Foot of the Blue Ridge, Virginia," *Virginia Geol. Survey, Bull. 17*, 1919 (map in pocket).

[20] *Virginia Geol. Survey, Bull. 17*, 1919, p. 29.

in the amount of forward movement of the core, the sort of differentiation of movement that deserves being emphasized. Here also we find the pre-Cambrian involved in rather small, sharp folds mantled by Cambrian sediments, like the one northeast of Lexington,

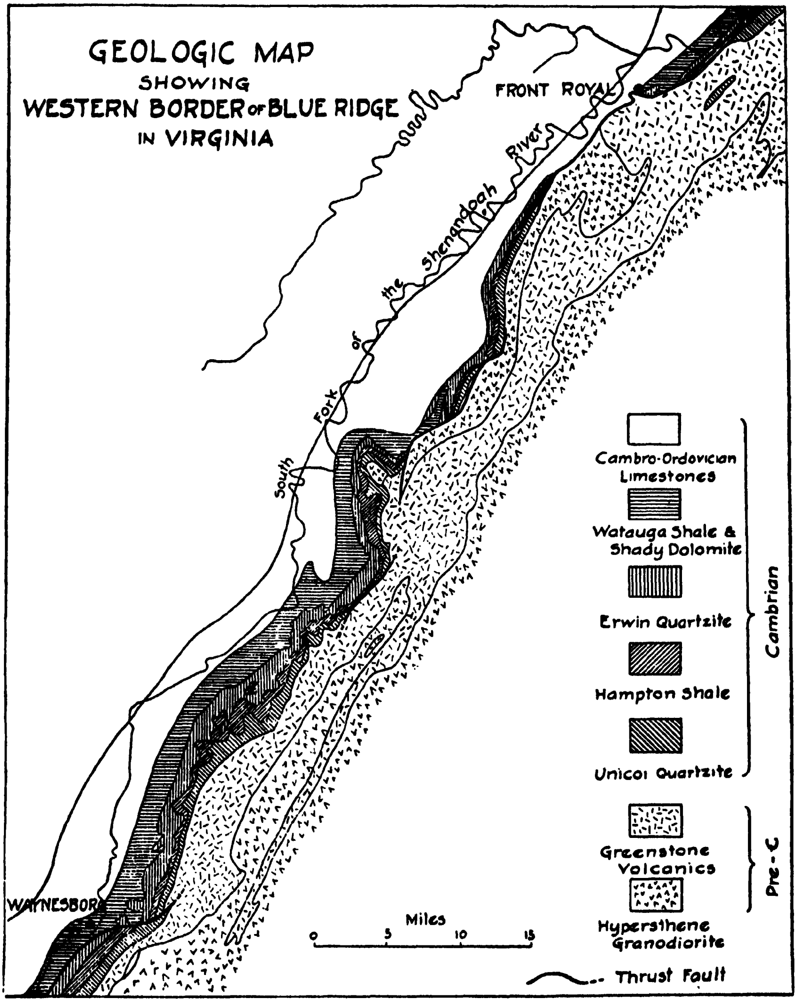


Fig. 45. Geologic map of a portion of the west foot of the Blue Ridge, Virginia.
(Redrawn, with slight changes, from G. W. Stose, H. D. Miser, F. J. Katz, D. F. Hewett, 1919)

Va., or the well known anticline of the James River gorge. In both of these a pre-Cambrian granitic rock (hypersthene granodiorite) forms the core of the fold. This capacity of the massive crystalline rocks to yield to the folding force requires special emphasis.

In Fig. 45 thrust planes have been indicated only where the original showed them as definitely observed. In the original, dashed lines, with occasional question marks, connect all the observed thrust planes back within the crystalline core. The current views concerning thrust faults demanded that the local thrust planes observed be all parts of a continuous "master fault." From our sketch it is evident that the reality of such a continuous thrust plane is not established. In less deformed welts we have seen thrust planes arise and die out in relatively short distances. It is entirely possible that the same is true here and in even more intensely disturbed regions. Heritsch,[21] for instance, has suggested such a differential local movement along the center of a thrust fault which dies out at the ends, for the immensely complicated structure of the northern calcareous portion of the Eastern Alps. We have no means of deciding with the meager information at hand whether the thrust planes in the Blue Ridge in Virginia are continuous or not. Even if they are, there still remains a great variation from point to point in the distance of forward movement beyond the edge. Such differential behavior implies a degree of "plastic" yielding which we do not associate habitually with the crystalline cores of welts.

This stretch of the west front of the Blue Ridge welt is not essentially different from the Rocky Mountain front. There is more deformation, but it is of the same nature. Farther south the intensity of deformation increases. The geologic map of Virginia shows remarkable overlaps of the crystallines onto the Cambrian foothills, especially southwest of Roanoke and near the Tennessee line. Along the same front low-angle thrusting reaches unusual dimensions farther out in the sedimentary formations of the valley. This is beautifully shown on the map by the "embayments" and "fensters" of Paleozoic formations within the broad lobe of overlapping Cambro-

[21] Fr. Heritsch, "Die Anwendung der Deckentheorie auf die Ostalpen II," *Geol. Rundschau*, Vol. 5, 1914, pp. 287-8. From the picture of an arc held fast at the ends and free to move in the center, Heritsch derives the term "aufgehängte Ueberschiebungsbögen."

Ordovician rocks, in Pulaski, Montgomery and Botetourt Counties. The complex imbricated structure shown on the map in Roanoke Folio, Tennessee, is generally known. Here the displacement along the Buffalo Mountain thrust fault has been at least twelve miles and may have been as much as twenty miles.[22] The extent to which the pre-Cambrian rocks have been thrust across the Paleozoic folds all along the eastern front of the Blue Ridge welt in Tennessee is shown in an impressive way on the geologic map of Tennessee.[23]

Eastern edge of Blue Ridge welt. The western edge of this Blue Ridge welt is sharply defined and generally recognized. The eastern border is by no means obvious. We turn again to the northern part of the Blue Ridge in Virginia as shown on the geologic map. Here the outermost rock of the pre-Cambrian structure is a mantle of metabasaltic lava flows, the "Catoctin greenstone" series. Beneath the Cambrian formations, this greenstone series forms an outer belt on the northwest side of the welt. Beneath it older metamorphics and later intrusives make their appearance. Rarely a narrow zone of Cambrian sediments is seen sharply infolded into rocks of the crystalline basement as, for instance, along the C. and O. Railroad, ten miles west of Charlottesville. Then, some fifteen to twenty miles southeast from the west front of the Blue Ridge, the Cambrian formations again form a distinct belt, associated as before with the Catoctin greenstones. The belt over which the Cambrian formations outcrop on the southeast side is much wider than that of the northwestern front. This would suggest the gentle southeast flank of an asymmetrical welt overturned toward the northwest. But the structure is much more complicated and requires a special explanation. We find here neither gently dipping beds such as cover the west side of the Bighorn Mountains, nor recumbent folds and thrust faults directed toward the outside of the welt, that is, in this case, southeastward.

Instead, we find the Cambrian beds in sharply compressed synclines mostly overturned toward the northwest. Beyond this belt of Cambrian synclines, blue slaty limestones of Ordovician age make their appearance east of Charlottesville in a zone about forty-five miles long and about two miles wide. At the northern end of this "Everona[24] lime-

[22] Arthur Keith, *Roan Mountain Folio, No. 151*, p. 9.
[23] *Geologic Map of Tennessee*, 1:500,000, State Geological Survey, 1923.
[24] A. I. Jonas, *op. cit.*, p. 842.

stone" zone the Ordovician rocks lie hidden beneath Triassic sediments. They become visible again on the Potomac River. North of the river they form the limestone valley of Frederick, Md. Going still farther north, we find them again concealed by Triassic beds. When they reappear, they form the well known limestone "valleys" of Hanover, York, and Lancaster in Pennsylvania. This synclinal zone marks the eastern border of the Blue Ridge welt.

The Martic thrust fault. The structure of the Blue Ridge welt manifestly is that of an "anticlinorium." As such it has been long described. The term "anticlinorium" represents a geometrical concept. Speaking of it as a "welt" makes us visualize the structure in terms of crustal dynamics. The peculiarity of this welt, compared with the simpler ones studied before, is the overturning of the sharp folds on both sides of the welt in the same direction toward the northwest. In an isolated welt, such a structure would be difficult to explain. Here the reason for it is found in the structure of the crystalline complex south of the Everona limestone belt. Fig. 46,[25] shows the nature of the southern border of this zone. Along its whole length the pre-Cambrian Wissahickon mica gneiss is thrust across the Ordovician limestones. Exactly the same relation is found along the southeastern edge of this synclinal zone along its whole length from Charlottesville, Va., to the Chester Valley in Pennsylvania. In Chester County, Pa., Bliss and Jonas have shown that the gneiss must have overridden the Paleozoic folds to a distance of over fifteen miles at least.[26] Fig. 47 illustrates the front of the Martic thrust fault, as this thrust is called, south of Chester Valley, west of Coatesville, Pa.[27] At the northwest end of the section, the south edge of a part of the Highland welt shows, which corresponds to the Blue Ridge welt farther south. The first wide outcrop of limestone is represented by the Chester Valley here about two miles wide. Beyond that the Martic thrust mass is seen lying in erosion fragments on top of the Paleozoic formations. The amount of displacement is impressive. There is

[25] Reproduced from A. I. Jonas, "Geologic Reconnaissance in the Piedmont of Virginia," *Bull. Geol. Soc. America,* Vol. 38, 1927, Fig. 1, p. 839. See also *Geologic Map of Virginia.*

[26] E. F. Bliss and A. I. Jonas, "Relation of the Wissahickon Mica Gneiss to the Shenandoah Limestone . . . ," *U.S. Geol. Survey, Prof. Paper 98,* 1916, p. 27; also map, Pl. I, opp. p. 10 and sections, Pl. III, opp. p. 26.

[27] E. F. Bliss and A. I. Jonas, *op. cit.,* Pl. III, section *A-A*

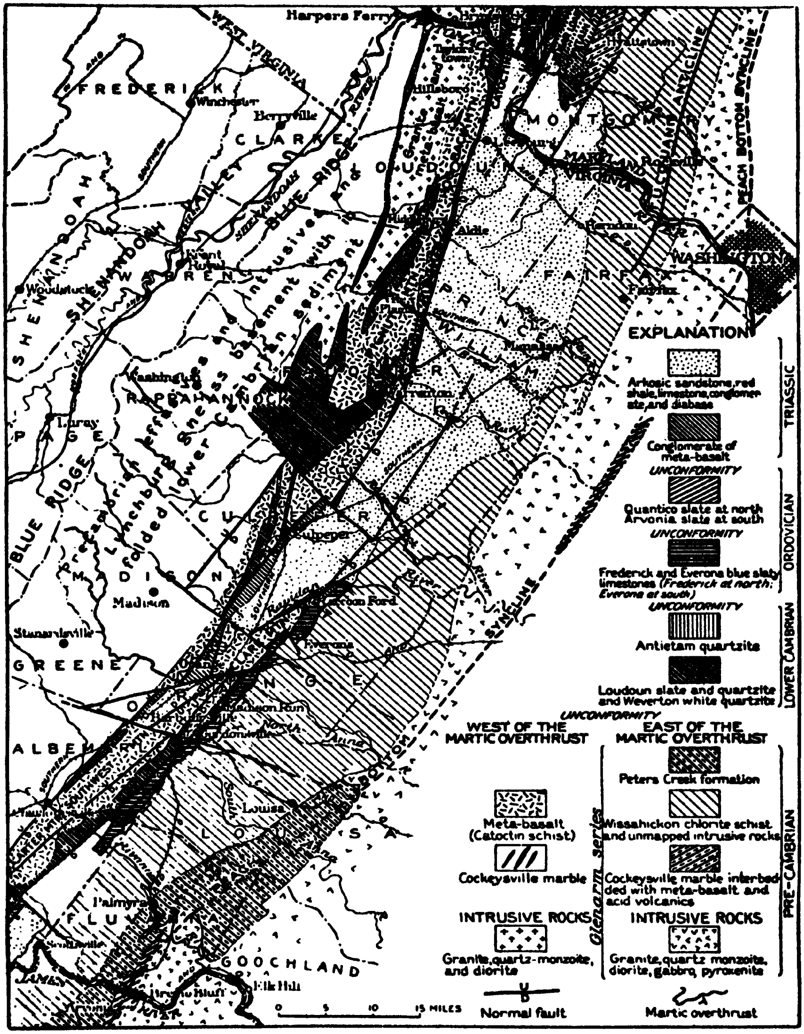


Fig. 46. Geologic map of northeastern Virginia.

For a quick orientation, note the following units: The stippled areas with the associated longitudinal and transverse faults represent Triassic sediments superimposed on the older structures. A narrow synclinal belt of Ordovician slaty limestones (marked by heavy horizontal ruling) extends from the southwest up to this cover of Triassic rocks and emerges at its northern border, close to the edge of the map. The eastern border of this syncline is formed by the *Martic overthrust,* along which pre-Cambrian schists are thrust on the Ordovician limestones. A second syncline of Ordovician rocks lies near the eastern edge of the map.

(A. I. Jonas, 1927)

reason to believe that the displacement along this Martic thrust fault increases toward the southwest.

Here, then, we have the border thrust of a second welt, probably of greater dimensions than that of the Blue Ridge welt. From Philadelphia to Charlottesville the front of the Martic thrust fault, as preserved today, approaches the east side of the crystalline core of the Blue Ridge welt more and more. South of Charlottesville, Va., it must have overriden the eastern border. Here today the two thrust blocks are separated by a post-Paleozoic normal fault. It is precisely from this point south, that the deformation of the Blue Ridge welt, especially the marginal thrusting on its west front reach greater dimensions, so that "along a section of the Appalachian belt from Raleigh, N.C., through Roanoke, Va., to the West Virginia line there is not an autochthonous block."[28]

Clearly, then, the folds of the southeast side of the Blue Ridge welt are overturned toward the northwest, because the front of the Martic welt, as we may call it, was pressed against them. How wide the Martic welt was when it arose or how wide it is now, after deformation, cannot be decided. A synclinal belt of slates in which Ordovician fossils have been found, lies some fifteen to twenty miles east of the outer edge of the Martic overthrust (Fig. 46). It seems likely that it is merely one of the pinched-in synclines which are part of every "anticlinorium." In that case it would correspond to the synclines of Cambrian rock in the core of the Blue Ridge welt. Yet it does not seem impossible that it may represent a major syncline separating two cores of such

Fig. 47. Structure-section across the Chester Valley syncline two miles west of Coatesville, Pa. At the northwest end of the section, Baltimore gneiss forms the northern border of the Chester Valley limestone belt which is bounded on the southeast by the trace of the thrust fault. (E. F. Bliss and A. I. Jonas, 1916)

[28] A. I. Jonas, "Structure of the Metamorphic Belt of the Central Appalachians," *Bull. Geol. Soc. America,* Vol. 40, 1929, p. 507.

dimensions as to deserve being called "welts." The structure of the Piedmont belt is without doubt far more complicated than has been assumed in the past. A large and fascinating field of inquiry lies here at our door. While the analytical study of textures and structures of metamorphic formations is being pushed actively in Europe, this field lies almost untouched though within easy reach of the numerous students in our eastern universities. The fine results achieved by Dr. Bascom and her students have given us the first perspective which will draw others into this rich field. For the time being at least we must turn to Europe for a further understanding of profound deformation in welts.

5. The Western Alps

Few regions in the world have been studied in such detail by such a large number of enthusiastic investigators as the Alps. Here Lugeon and Schardt at the threshold of the new century found the clue to the solution of a bewildering array of structures and thereby introduced one of the most far-reaching revolutions into geological thought.

The Map. Fig. 48 shows in diagrammatic fashion the larger structural units of the Alps. It is reproduced from von Bubnoff's[29] valuable introduction to the problems of Alpine tectonics. Since we shall not enter here into a discussion of the structural problems of the Alps as a

[29] S. von Bubnoff, *Die Grundlagen der Deckentheorie in den Alpen,* Stuttgart, 1921, Fig. 12, p. 24.

By far the best introduction to Western Alpine geology is contained in Vol. II of Alb. Heim's *Geologie der Schweiz,* Leipzig, 1921 (Part I) and 1922 (Part II). Here all facts are given in detail and yet coordinated in such a fashion that their bearing on the broader problems of structure is developed systematically. The only English introduction to Alpine structure is L. W. Collet's *The Structure of the Alps,* London, 1927.

Of the outstanding discussions of Western Alpine structure the following may be quoted here:

H. Schardt, "Les régions exotiques du versant nord des Alpes suisses," *Bull. soc. vaud. sci. nat.,* Vol. 34, Lausanne, 1898; M. Lugeon, "Les grandes nappes de recouvrement des Alpes suisses," *Congr. géol. internat.,* IX, 1903, *Compt. Rend.,* pp. 477-506; P. Termier, "Les nappes des Alpes orientales et la synthèse des Alpes," *Bull. Soc. Géol. France,* 4ème sér., Vol. 3, 1904; G. Steinmann, "Geologische Probleme des Alpengebirges," *Zeitschr. deutsch. oester. Alpenver.,* Vol. 37, 1906; C. Schmidt, "Bild und Bau der Schweizeralpen," *Beil. z. Jahrb. d. Schweiz. Alpenklubs,* Jahrgang 42, 1906-07, Basel; E. Argand, "Sur l'Arc des Alpes occidentales," *Eclogae geol. Helvet.,* Vol. 14, 1916, pp. 145-91.

Two syntheses of the Alps as a whole, both with large tectonic sketch maps: L. Kober, *Bau und Entstehung der Alpen,* Berlin, 1923; R. Staub, "Der Bau der Alpen," *Beitr. z. geol. Karte d. Schweiz,* N.F., Lief. 52, Bern, 1924.

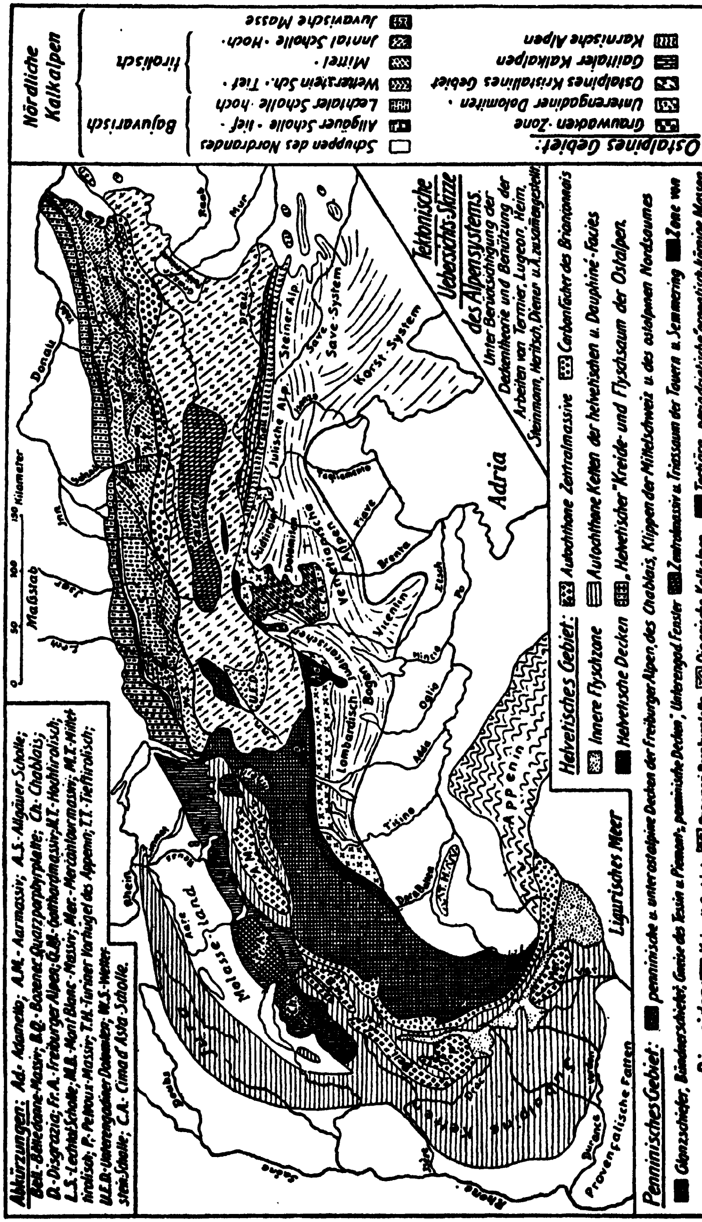


Fig. 48. Tectonic sketch map of the Alps.
For a discussion of the Western Alps see pp. 181–99 of this book. For the Eastern Alps the reader is referred to the original.
(S. von Bubnoff, 1921; reproduced from *Die Grundlagen der Deckentheorie in den Alpen*, by permission of E. Schweizerbart'sche Verlagsbuchhandlung [Erwin Nägele])

whole, the elaborate legend reproduced with the map has not been translated. The units that concern us here will be explained in these pages. The reader who wishes to study the map as a whole, may refer to the original or to the excellent brief discussion of this map in S. von Bubnoff, "Ueberblick über den geologischen Bau von Europa."[80]

The map brings out clearly the structural contrast between the Eastern and Western Alps. The meridian of the east end of the Lake of Constance marks approximately the boundary. We shall concern ourselves only with the Alps west of this dividing line.

The Aar massif, one of the autochthonous massifs. In order to find a basis for a comparison of Alpine structure with that of the American welts discussed above, let us go into the Alps from the north, say from Basel, travelling in a southeasterly direction. We pass over the marginal folds in Mesozoic and Tertiary rocks which constitute the Jura Mountains, the northern Swiss Basin and the northern Calcareous Alps, until we reach the first zone within the Alps in which the crystalline substructure has been brought within reach of erosion. This we find in the celebrated chain of snow-capped peaks which extends from the Jungfrau in the south to Tödi Mountain in the north, through the cantons of Bern, Uri, and Glarus. In Alpine literature this is known as the Aar Massif, named after the deep gorge of the Aar River which cuts it. We shall here speak of it, for purposes of comparison, as the Aar welt.

In Fig. 49 are reproduced three of twenty cross-sections, arranged serially, which constitute Plate VII of Heim's *Geologie der Schweiz.*[81] Turn to the first of these sections. The upper part of the pyramid of Tödi Mountain consists of Upper Jurassic limestones. The heavy black line which runs through the center of the mountain marks the basal formations of the Mesozoic series. These thin Middle and Lower Jurassic and Triassic formations rest with a strong angular unconformity on the pre-Triassic crystalline rocks. The section shows at once that the steep dips within the crystalline rocks are not the result of the Alpine folding at all. On the north side of Tödi Mountain, for instance, at the place marked Sandalp in the section, an arrow with the letter *C* points to two sharp synclines of Carboniferous

[80] In Wilhelm Salomon, *Grundzüge der Geologie,* Vol. I, Stuttgart, 1924, pp. 791-839 ("The Alps," pp. 816-29).

[81] opp. p. 144. Sections 3, 10, 15 are here reproduced.

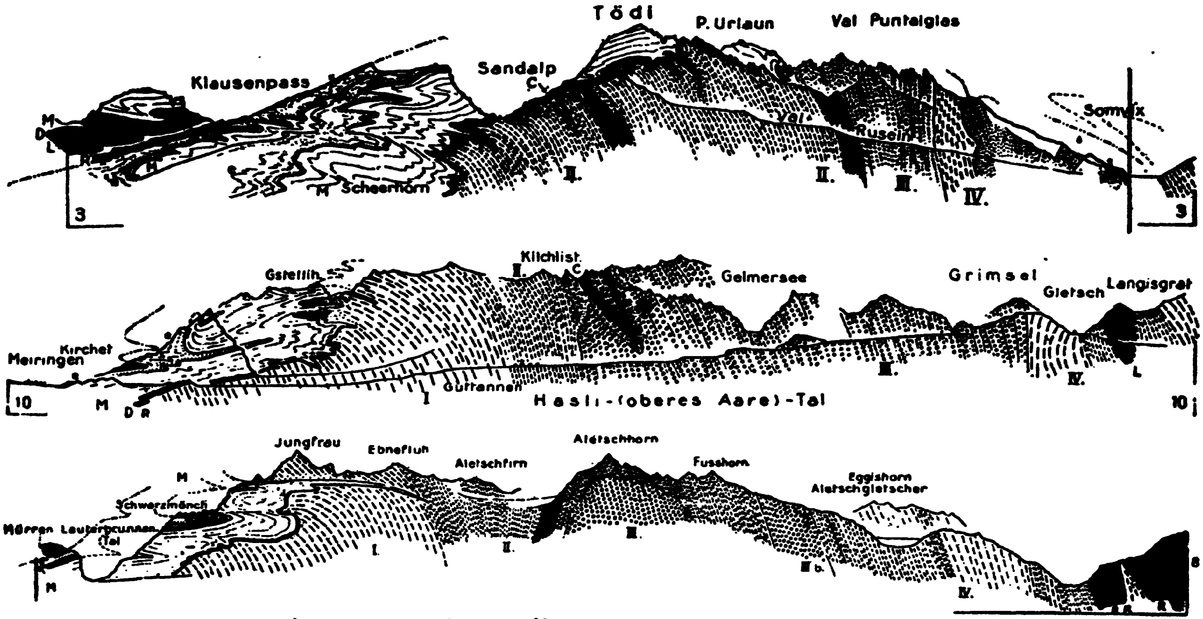


Fig. 49. Three structure-sections across the Aar massif.

Symbols: I. Steeply dipping rocks of crystalline core:

II = Northern belt of sericite schists and gneisses with amphibolites (black with white dashes)

III = Central zone of granitic rocks

IV = Southern belt of gneisses and schists (finer dashes) with diorites (finely stippled)

2. Sedimentary rocks lying unconformably on crystalline: *black* = Triassic (*R*), Lower and Middle Jurassic formations (*B* = schistes lustrés; *L* = Lias; *D* = dogger); *white* = Upper Jurassic (*M* = Malm), Cretaceous (*K*), and Eocene (*e*). In the top section, Upper Carboniferous rocks (*C*) appear beneath the Triassic rocks.

(Alb. Heim, 1921; reproduced by permission of Bernhard Tauchnitz A. G.)

rocks. Here sericitic slates containing Middle Pennsylvanian fossils are associated with sandstones and conglomerates and thin bands and lenses of anthracite. The pre-Triassic peneplain cuts across these synclines (and many others in this region) and on it the marine Mesozoic sediments have been deposited. The base of the Pennsylvanian rocks, however, is seen to lie in turn unconformably on the older rocks of the intensely compressed crystalline basement.

This structural relation is identical with that exposed where north or west of the Alps the crystalline basement has been brought into view in broad swells. In the Black Forest, for instance, coal-bearing Pennsylvanian formations and Permian red beds with porphyritic lava flows[32] lie uncomformably on a pre-Pennsylvanian peneplain which bevels the metamorphic formations and intrusives of greater age. They occupy narrow trough-like depressions in which they lie only slightly folded or broken by insignificant tension faults. They themselves are beveled by the remarkably even pre-Triassic erosion surface,[33] on which the great series of Triassic and Jurassic rocks lies unconformably.

In this northernmost of the Alpine welts, then, the crystalline substructure of south central Europe has been brought to the surface as it is seen in the swells farther north, only much more deformed here, within the mobile belt.

We are here especially concerned with the structural expression of this more intensive deformation. The first of the three sections reproduced in Fig. 49 shows the sedimentary mantle thrown into crowded dragfolds. The form of these dragfolds implies that they must have been produced by a mass thrust over them, now removed by erosion. West of the Klausenpass, in fact, is seen a remnant of that thrust mass consisting of Triassic and Jurassic formations resting abnormally on Eocene beds. These same Eocene beds, the youngest sediment in the folded structure of the Alps, lie in place on one of the neighboring peaks, the Bifertenstock, 11,240 feet above sea level (3,426 meters) which marks the highest elevation of nummulite-bearing Eocene in Switzerland and one of the highest in the Alps.

[32] A Permian porphyry is seen locally in similar position in the Aar massif, e.g., in Windgälle Mountain, section 5, Pl. VII, of Heim's *Geologie der Schweiz*.

[33] Described in a fine monograph by A. Strigel, "Zur Palaeogeographie des Schwarzwaldes," *Verh. Naturwiss. Ver. Heidelberg*, Beilageheft zu N. F. Bd. 15, Frankfurt a. M. und Heidelberg, 1922.

The contact of the Mesozoic sediments with the crystalline substructure is most illuminating. The sections show the crystalline basement forced up in the form of sheared slices which force the basal beds of the Mesozoic series into sharp folds. In the second section which lies southwest of the first, the infolding of the Mesozoic sediments in the crystallines has assumed altogether the character of "plastic" deformation. The Gstellihorn, shown in this section, is one of the most famous localities in the Alps. Here the Jurassic limestone is kneaded into the gneiss of the substructure in long drawn-out folds and pinched-off lenses (Fig. 50).[84]

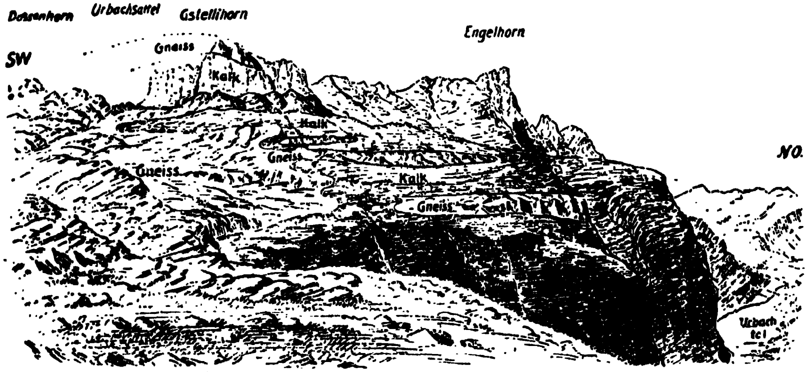


Fig. 50. View of the Gstellihorn in the Bernese Alps (seen from the southwest), showing recumbent folds of Jurassic limestone and gneiss. The contact of the two rocks is drawn out in such a way that the gneiss extends into the limestone in the form of narrow, long prongs, with synclines of limestone similarly penetrating into the gneiss.

(After Baltzer, from G. Steinmann, 1906)

The "plastic" behavior of the crystalline core and the differential movements within it are shown even more emphatically in the third section of Fig. 49, which cuts the famous peak of the Jungfrau. The tourist who has seen the Jungfrau from Mürren or the Lauterbrunnen Valley is familiar with the horizontal position of the bedded formations which traverse the broad mountain front like ruling by an artist's pen. The appearance of an undisturbed position of the limestone layers is perfect. But a view at right angles, such as is given in this section, shows that the tourist is looking at the edges of recum-

[84] Reproduced from Fig. 7, p. 15, in G. Steinmann, "Geologische Probleme des Alpengebirges," *Zeitschr. Deutsch.-Oesterreich. Alpenvereins,* Vol. 87, 1906, pp. 1-44.

bent isoclinal folds. The gneiss of the peak has overridden the limestone series, squeezing them into a narrow syncline beneath them. Yet there is no trace of an inversion of the planes of schistosity[35] in the gneiss of the recumbent anticline such as would have resulted if the fold had been developed step by step from a normal, open symmetrical anticline. To the contrary, the schistosity remains quite constant, that is, the lower limb of the anticline marks a line along which differential movement forced the gneiss forward, drawing it out but not reversing its inner structure.

In Fig. 51 details of the contact are shown according to the careful

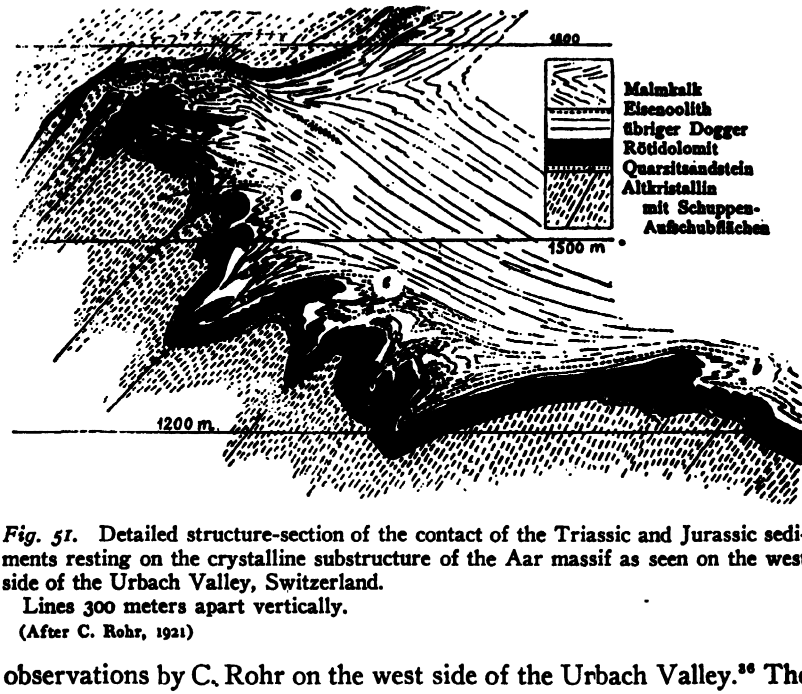


Fig. 51. Detailed structure-section of the contact of the Triassic and Jurassic sediments resting on the crystalline substructure of the Aar massif as seen on the west side of the Urbach Valley, Switzerland.
Lines 300 meters apart vertically.
(After C. Rohr, 1921)

observations by C. Rohr on the west side of the Urbach Valley.[36] The quartzitic sandstone at the base lies in angular unconformity on the steeply dipping schistosity of the crystalline basement. The attitude of the sandstone marks the differential advance of the crystalline

[35] The lines indicating the planes of schistosity in the section are not diagrammatic but correspond to observed conditions.

[36] Reproduced from Fig. 248, p. 932, of Heim's *Geologie der Schweiz,* Vol. II (C. Rohr, 1921).

mass. The details of the structure of the Triassic Röti dolomite are the result of differential movements between the more plastic Jurassic limestones and the less plastic dolomite. At "a" the dolomite is simply thickened along the anticlinal crest and the limbs are correspondingly reduced. At "b" the thickness of the Middle Jurassic (Dogger) limestone is greatly reduced above the swelled dolomite and accumulated as a complexly crumpled mass on the lee side of the swelled crest. This is repeated at "c." Here, however, a slice of the Roti dolomite is forced down into the crystalline mass at the left end by the highly plastic Jurassic limestones and sheared off at the other. All this complication of secondary and tertiary folds is the result of differential movements caused by differences in the plastic behavior of the sedimentary formations below the Malm limestone.

In Fig. 52,[87] Heim has represented in diagrammatic form the different types of structural relations which characterize the contact of the sediments with the crystalline basement. Note the fold of dolomite sheared off the contact at point 7. Note especially the mass of Mesozoic sediments squeezed off at the bottom of the syncline within the crystallines (lower point 6), and a corresponding lobe forced off the main body of the crystalline rock and embedded in the sediments (upper point 6). Fig. 53[88] shows one of these deep squeezed-off synclinal cores of sedimentary rock, largely limestones. It is 650 to 800 feet wide and its lowest point lies nearly 10,000 feet below the surrounding peaks of sericitic schists and amphibolites of the pre-Triassic mass. Yet the sediments show merely signs of mechanical deformation with only insignificant mineralogical changes. The stratigraphic sequence can readily be made out and is entirely normal. Fossils are abundant but are, of course, badly deformed. The fine examples of stretched belemnites which Heim figures on Pl. III of the second volume of his *Geologie der Schweiz*, are from this locality.

In all the features described above, we see the differential, localized advance of the crystalline core of a welt carried to a greater extent than in the Blue Ridge in Virginia or the Rocky Mountain front. Here also we have abundant evidence of thrust masses having been pushed across the welt from the south. They give the foreland of the Alps its structural characteristics. Since they form an essential part

[87] Reproduced from Fig. 49, p. 157, of the *Geologie der Schweiz*, Vol. II.
[88] Reproduced from Pl. VIII, opp. p. 164, of the same work.

of the evidence concerning the mechanics of Alpine deformation we will consider them first before going south into the heart of the Alps where deformation was more intense just as it was found to have been in back of the Blue Ridge welt in the Appalachians.

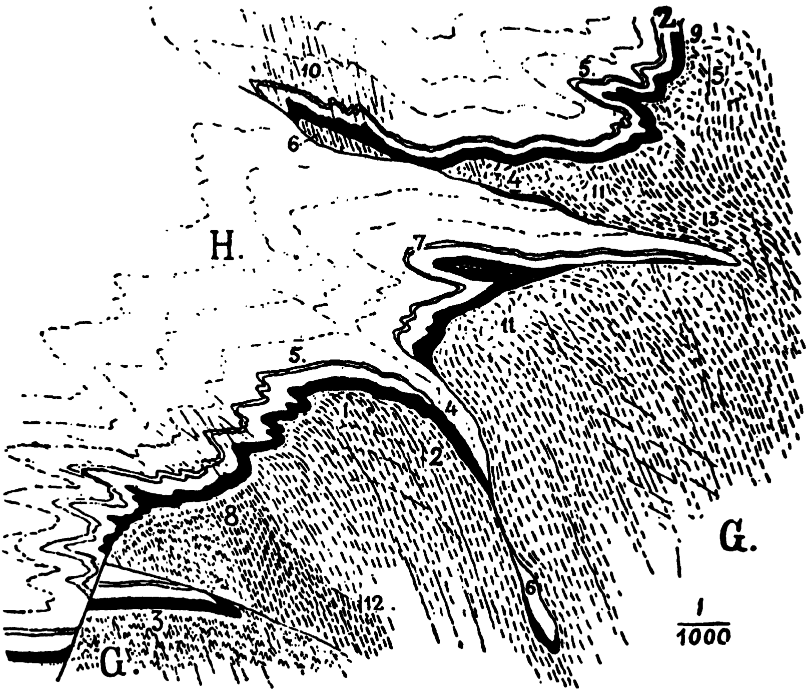


Fig. 52. Diagrammatic structure-section showing the deformation of the contact zone of sediments resting with angular unconformity on the crystalline substructure of the Aar massif, Switzerland.

G = crystalline rocks.
Z = Triassic to Middle Jurassic rocks (sandstones, dolomites, etc.).
H = Upper Jurassic limestone ("Hochgebirgskalk").

(Alb. Heim, 1921; reproduced from *Geologie der Schweiz*, by permission of Bernhard Tauchnitz A. G.)

The autochthonous massifs in general. First let us look again at the map, Fig. 48. The Aar massif is marked "A M" and bears the pattern of "autochthone Zentralmassive." They are called "autochthonous" not because here the Mesozoic sediments are exposed resting *in situ* on the old pre-Permian basement, but because the crystalline core itself apparently is still essentially in place in contrast to the

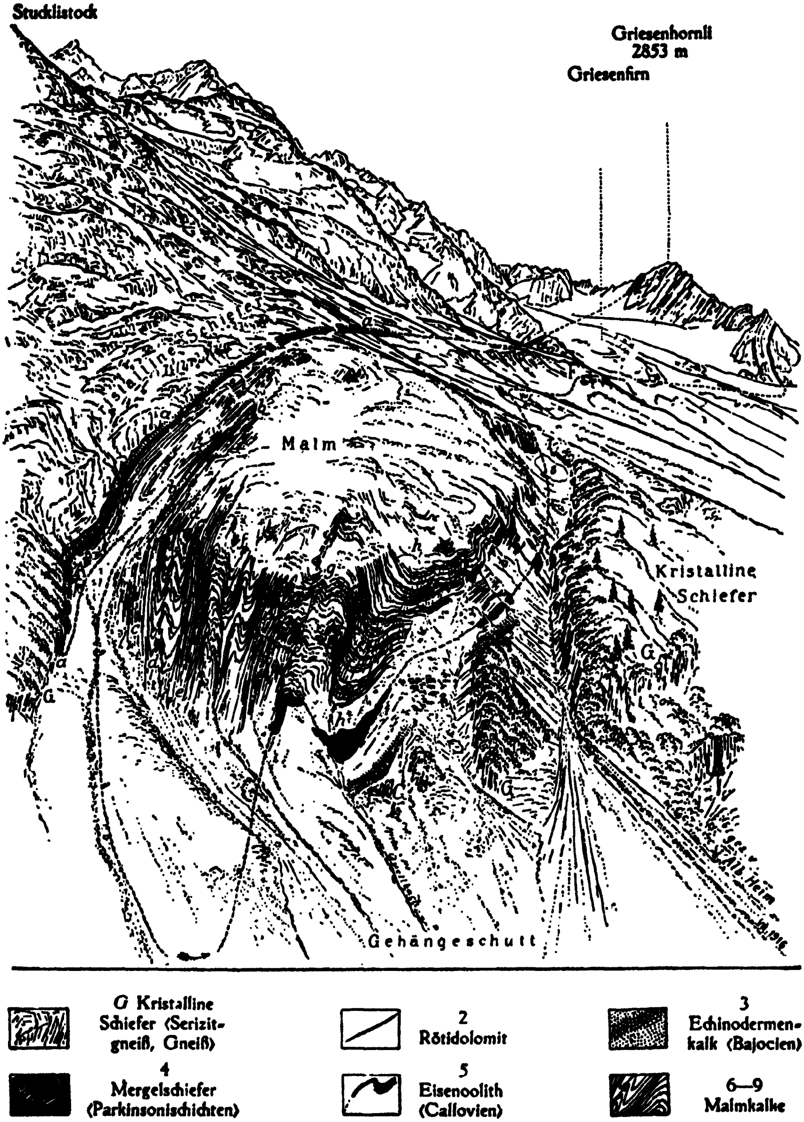


Fig. 53. Narrow syncline of Upper Jurassic limestone (underlain by older Mesozoic rocks, shown by heavy black line) sharply infolded in the crystalline rocks of the Aar massif, near Fernigen, Switzerland.

(Alb. Heim, 1921; reproduced from *Geologie der Schweiz*, by permission of Bernhard Tauchnitz A. G.)

crystalline masses in the heart of the Alps. The map shows that the line of these autochthonous massifs follows the northern border of the Alps through the Mont Blanc massif, that of Belledonne and Pelvoux down to the massif of Mercantour in the Maritime Alps. The outcrops of the crystalline cores are not continuous at the present erosion levels. They mark maxima of rise along the welt axis separated by minima, in harmony with our law 7.

The decken of the northern foreland. Surrounding these autochthonous crystalline massifs, the map shows belts of autochthonous chains of Mesozoic and Eocene rocks ("autochthone Ketten der helvetischen und Dauphiné Facies"). They correspond to the folds in the foothills of our Rocky Mountains and the Paleozoic folds of the Appalachian west front. They should merge northward into the Tertiary "Molasseland" where the folding dies out gradually. Instead, we find a belt of *decken,* of intensely folded Mesozoic rocks thrust northward onto the Mesozoic-Eocene rocks of the foreland. The main body of this zone is marked on the map as "Helvetische Decken." These have been derived from the top and the south side of the northernmost zone of welts. But they themselves, in turn, are overlain by foreign thrust masses which by their position and facies show that they have been derived from still farther south, from the inner regions of the Alps. These bear the label "Penninische und Unterostalpine Decken." North of the Aar massif this upper story of thrust masses appears only in isolated patches, the "Klippen" of the Swiss geologists. The two peaks marked "Mythen" on Fig. 54 represent the most famous of these "Klippen."[89]

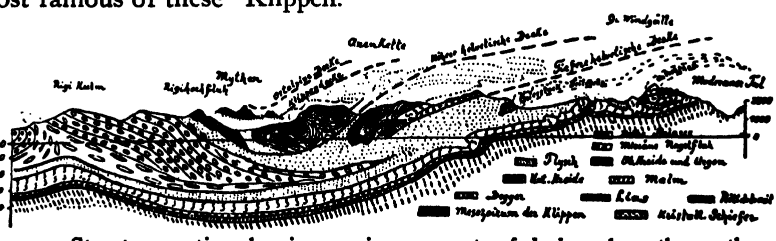


Fig. 54. Structure-section showing erosion remnants of *decken* along the northern border of the Swiss Alps, pushed onto the tilted Miocene conglomerates of the foreland (as seen on the east side of the Lake of Luzern).

(S. von Bubnoff, 1921; reproduced from *Die Grundlagen der Deckentheorie in den Alpen,* by permission of E. Schweizerbart'sche Verlagsbuchhandlung [Erwin Nägele])

[89] Reproduced, after Buxtorf, from S. von Bubnoff, *Die Grundlagen der Deckentheorie in den Alpen,* Stuttgart, 1921, Fig. 18, p. 32.

North of the wide gap between the Aar and Mont Blanc massifs these higher thrust masses are preserved in continuous sheets. There they form the mountains of the "Préalpes," northeast and southwest of the Rhine Valley ("Freiburger Alpen" and "Chablais" on the map). In the gap between the two massifs thrust masses of sediments lie piled in astonishing thickness.

It is significant that the arc of the Jura folds curves around this gap and the Préalpes in front of it. On an earlier page the evidence has been given which shows that the folds of the Jura Mountains were sheared off the Triassic basal formations. Such superficial shearing-off of so thin a skin of sediments is possible only through the friction exerted by a mass thrust onto the surface. It seems entirely reasonable to see the source of this friction in the exceptional thrust masses that lie piled in the gap and in front of it, represented graphically by the Préalpes.

The map suggests the presence of a second sweeping arc comparable to that of the Jura Mountains opposite the gap between the massifs of Pelvoux and Mercantour. This impression is false. The folding of the Mesozoic sediments in the French sub-Alpine chains is not concentric with the outline of the shaded area. We do not need to concern ourselves with them here.[40] Yet we may note that here too as through "a gateway the impelled mountains make their exit to the west, just as water or ice, furrowing away the ground beneath it, forces its way through a constricted passage."[41] Here the closely packed folded masses which have advanced onto the foreland consist largely of Flysch, carrying upon them fragments of *decken* of inner-Alpine Mesozoic rocks.

The south side of the zone of autochthonous massifs. We have seen that the structure of the foreland north of the autochthonous massifs is dominated by the advance of *decken* which were forced across the zone of massifs from an original position south of it. Here more even than in the Blue Ridge welt we should expect the rear slope of the welts to be intensely deformed and overturned in the direction of the pressure from within the mountain arc. Indeed, all details of structure testify to the pressure that was brought to bear against them from

[40] A tectonic sketch of this region, published by Kilian in 1909, is reproduced in E. Suess-DeMargerie, *La Face de la Terre*, Vol. III, Part 2, p. 703, Fig. 140.

[41] E. Suess, *The Face of the Earth* (trans. by Sollas and Sollas), Vol. IV, p. 114.

that direction. Heim states emphatically that all signs of compression, such as zones of shearing, of cataclasis and seritization, within the pre-Triassic crystalline rocks of the core increase in number as one passes from the Aar massif to the next massif, the welt of St. Gotthard[42] (*G.M.* on the map).

The Pennine Alps, zone of recumbent crystalline decken. The Gotthard massif is bounded on the south by the narrow, intensely compressed zone of Mesozoic formations, here metamorphosed into schists, the Bedretto syncline. South of it lies the heart of deformation in the Alps. Here, in the Pennine and Lepontine Alps, we find plastic deformation carried to the extreme.

For an illustration we turn to the region of the Simplon Tunnel. The Figs. 55 *a*, *b*, *c*, and *d*[43] show graphically the steps by which the structure of this classic region has become understood. A reconnaissance survey of the vicinity of the tunnel project in 1882 led to the rather simple interpretation illustrated by Fig. 55*a*. South of the Bedretto zone of phyllitic schists (*SK*) which separates this region from the autochthonous massifs, the structure suggested a simple broad anticline of schists and schistose gneisses with intercalated bands of limestones and dolomites, partly in the form of marbles. In 1893, Schardt, who afterwards took over the geological study of the tunnel during construction, interpreted the massive Antigorio gneiss as the core of an anticline recumbent toward the north, and the crystalline rocks north of it as a double anticline overturned toward the south. Schmidt's profile represents the same conception, but anticipates a solid core of gneiss. When the tunnel was cut, instead of some twelve miles of more or less continuous gneiss and schists, first isolated thin belts of limestones were met and these were followed for a distance of four kilometers by phyllites surrounded by a mantle of limestones before the Antigorio gneiss was reached. With the calcareous schists and limestones hot ground water came in, in unexpected quantities. When the tunnel was completed, the structure was recognized to be as shown in the last of the sections reproduced in Fig. 55. Lugeon was the first to reinterpret the tunnel section.[44] In 1905 Schmidt and

[42] *op. cit.*, Vol. II, p. 192.

[43] Reproduced from L. Kober, *Bau und Entstehung der Alpen*, Berlin, 1923, pp. 56-7, Figs. 21, 23, 25, 27.

[44] M. Lugeon, "Coupe géologique du Massif du Simplon," *Compt. Rend., Acad. Sci.*, Paris, 1902.

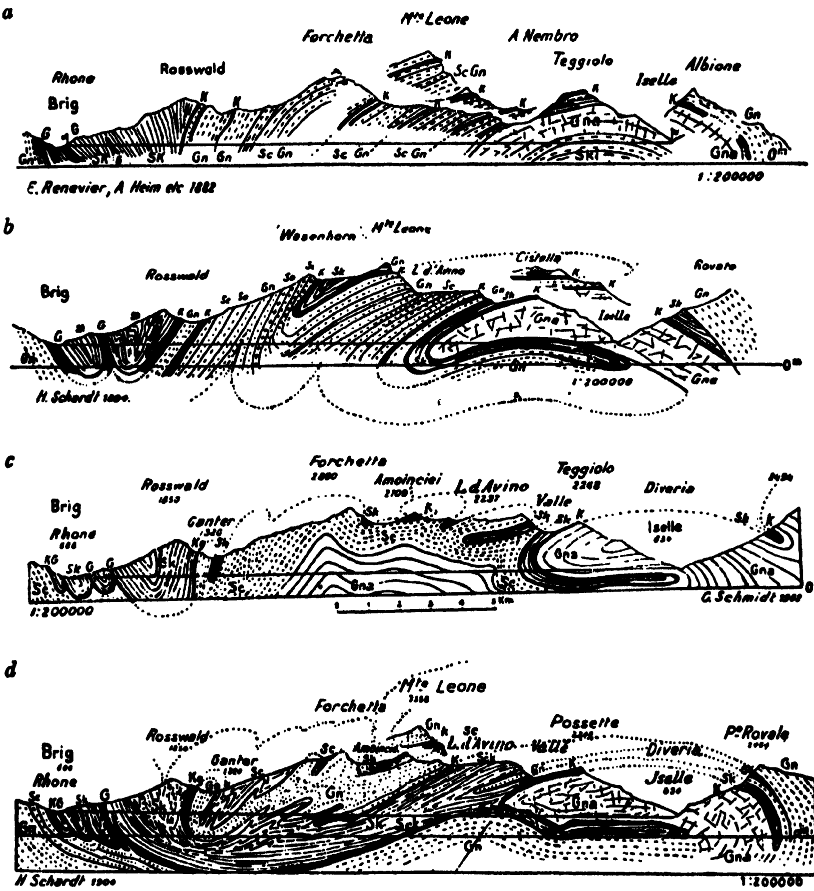


Fig. 55. Four structure-sections across the vicinity of the Simplon Tunnel in the Swiss Alps, illustrating the changes in the interpretation of the structure brought about by the construction of the tunnel.

Note that in all sections the outcrops at the surface are the same. Sections *a, b, c* represent interpretations made before the construction of the tunnel; *d* shows the interpretation demanded by the observations made during the construction of the tunnel.

(*a* = E. Renevier, 1882; *b* = H. Schardt, 1893; *c* = C. Schmidt, 1902; *d* = H. Schardt, 1904.)

Symbols: 1. *Older crystalline rocks. Gn* = gneiss; *ScGn* = schistose gneiss; *Gna* = Antigorio gneiss; *Sc* and *Ski* = mica schists; *Sa* = amphibolite schists.

2. *Sedimentary rocks, more or less metamorphosed. SK* = phyllitic shales (schistes lustrés); *K* = limestone, dolomite, marble; *G* = gypsum.

Preiswerk completed the geological map of the Simplon sheet and demonstrated that this interpretation of the tunnel section clears up successfully the structure of the whole region.[45] The diagram they drew brings out more definitely the extraordinary evidence of "plastic" behavior offered by this region. (Fig. 56.)[46]

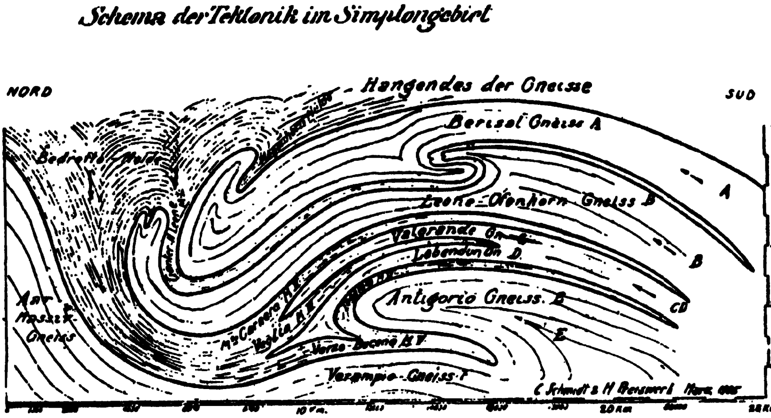


Fig. 56. Diagram showing the structure of the Simplon region reconstructed on the basis of detailed mapping and of observations made during the construction of Simplon Tunnel.

(Compare with Section *d* in Fig. 55.)

(C. Schmidt, 1907)

The outstanding characteristic of this section as well as of the whole Pennine region, is the absence of large thrust planes. All these *decken*, with a maximum distance of overfolding of fifty kilometers, are recumbent anticlines in which all members of the sedimentary series are present in the inverted lower limb though, of course, in immensely drawn-out condition. The broad, sharply curved front (crest) of the anticlines is well exposed in several of these Pennine *decken*.

Fig. 56 shows that none of the gneisses of this region are intrusive according to the evidence presented by the Swiss geologists. They are

[45] C. Schmidt and H. Preiswerk, *Karte der Simplon Gruppe*, 1:50,000, and "Erläuterungen," 1908.

[46] C. Schmidt, "Ueber die Geologie des Simplon gekietes und die Tektonik der Walliseralpen," *Eclogae geol. Helvet.*, Vol. 9, 1905. (The figure reproduced from C. Schmidt, "Bild und Bau der Schweizer Alpen," *Beilage z. Jahrbuch d. Schweiz. Alpenklubs*, Jahrg. 42, 1906-07, p. 48.)

all lobes of the pre-Permian crystalline basement. Six such gneiss *decken* lie one on top of the other in the region south of the Rhine. The highest of these culminates in the magnificent peaks of the Dent Blanche and the Matterhorn (Fig. 57).[47] Pre-Triassic schists,

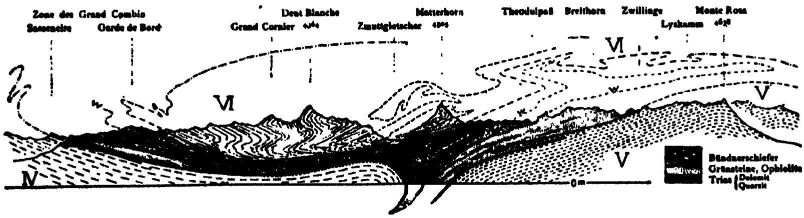


Fig. 57. Structure-section showing the highest of the pennine *decken* of the central Swiss Alps, the Dent-Blanche *decke.*

The Dent-Blanche *decke* (VI) consists of gneiss and other crystalline rocks. Between it and the gneisses of the underlying *decken* (IV and V) lies the squeezed-in recumbent syncline of Mesozoic rocks (Triassic and Lower Jurassic "Bündner-schiefer" = schistes lustrés with intercalated greenstones = ophiolites). Note that the Dent-Blanche *decke* has the character of a plastically folded recumbent anticline.
(E. Argand, 1911)

gneisses, and granites make up the bulk of this highest *decke* in the Pennine Alps. On its underside, in inverted order, can be seen the normal sequence of Triassic and Jurassic rocks reduced from a thickness of several thousand meters to one of twenty to thirty meters,[48] a reduction to-one-hundredth of the original thickness on the average. Within the *decke*, the pre-Triassic planes of stratification and schistosity are still visible, superseded but not destroyed by the structural effects of the last deformation.[49] It all looks as if the *decke* had flowed into its present form "like viscous dough."

As Figs. 55 and 56 show, throughout this region of Pennine *decken* bands of more or less calcareous phyllitic and micaceous schists with zones of marble lie wedged between and beneath the *decken* of pre-Triassic gneiss. These are the "schistes lustrés"[50] of the Swiss geologists, largely of Lower Jurassic age. They obviously played the

[47] Reproduced from Fig. 175, p. 538, of Heim's *Geologie der Schweiz,* Vol. II (after E. Argand, 1911).

[48] Alb. Heim, *op. cit.,* Vol. II, p. 538.

[49] *ibid.,* p. 539.

[50] "Glanzschiefer," "Bündener Schiefer" of the German Swiss, "Sk" and "Sck" in the sections figured above.

rôle of a lubricant and highly plastic filling medium. Their original thickness must have been at least 2,000 meters (6,500 feet) and may have been as much as 5,000 meters (16,000 feet). They mark the most steadily sinking part of the Mesozoic geosyncline in this part of the Alps.

In the sediments of this active inner-Alpine geosynclinal zone, as in other geosynclinal belts, greenstones ("ophiolites") are widely distributed. In the northernmost part of the Pennine region, they appear only as scattered layers in the "schistes lustrés." They increase in quantity as one passes southward and upward into those *decken* which must have laid originally farther south. Here the greenstones greatly predominate over the sediments. They are the products of metamorphism of basic intrusives and probably their lavas and tuffs, ranging from diorites and gabbros to dunites, pikrites, etc. They were intruded into the sediments of the geosyncline during the Mesozoic geosynclinal phase, mainly during Middle Jurassic time. Their present petrographic character is clearly the result of dynamometamorphism. If we compare the intensity of metamorphism of the greenstones, going from the zones which originally lay farthest north to those which occupied positions progressively farther south, we find that it increases steadily toward the south.[51] The maximum of compression, therefore, must have taken place south of the Pennine zone. This is to be expected. The recumbent folds of the Pennine region must represent crustal folds, welts forced out by compression to such an extent that they would have risen like thin laminae tens of miles high, if they could have stood up. Because of their plastic behavior, they crept forward as horizontal sheets. The zone in which they had their roots must, therefore, have been the seat of greatest compression.

Zone of vertical roots of folds. This region of "roots," south of the Pennine region, on the map (Fig. 48) bears the name "zone of Ivrea and Tonale." Here narrow lenticular bands of marble, gneisses and schists, associated with a variety of basic intrusives and their metamorphic equivalents, stand closely pressed in essentially vertical position. The dominant vertical attitude of the tectonic units in this zone is in strong contrast to the frequency of low dips north of it in the Pennine region of nearly horizontal *decken*. The evidence is strong that the marbles and other zones of greatly compressed sedi-

[51] Alb. Heim, *op. cit.*, p. 500.

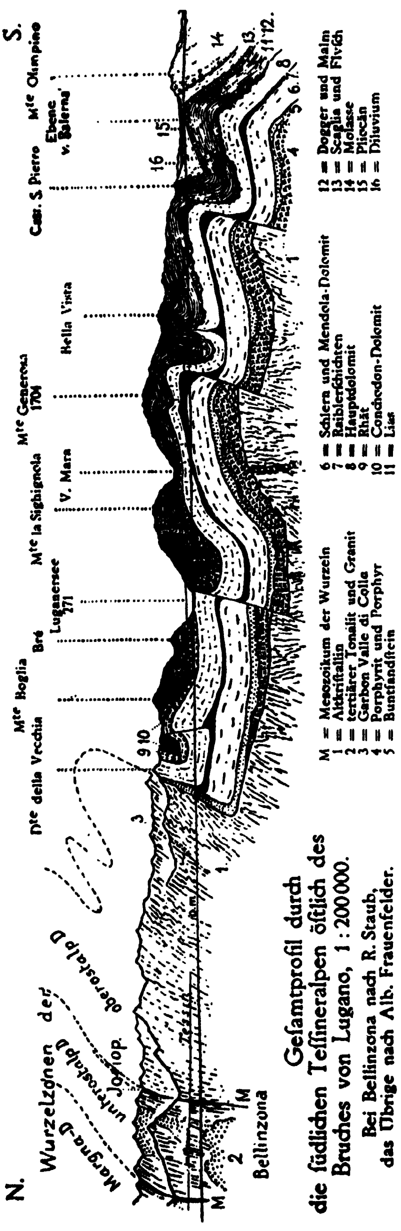


Fig. 58. Structure-section through the southern part of the Swiss Alps in the longitude of Bellinzona. Note the contrast between the northern third and the rest of this section. In the northern portion, narrow bands of Mesozoic rocks are squeezed in isoclinally (*M*) as synclines between the vertical "roots" of the anticlinal *decken* (*D*). In the southern part the Mesozoic mantle of sediments rests in broad folds on the little disturbed crystalline substructure. (After R. Staub and A. Frauenfelder, from A. Heim, 1922; reproduced by permission of Bernhard Tauchnitz A. G.)

mentary rocks are of Mesozoic age. They, then, represent the extreme tips or "roots" of synclines. The narrow bands of pre-Triassic metamorphism between them must be the roots from which have been squeezed the cores of the *decken* of the Pennine region. In Fig. 58,[52] the names of the *decken* indicate their roots, such as "Margna-D.," "unterostalp. D.," etc. The squeezed-in roots of the synclines of Mesozoic rocks are marked with the letter "M." The portion of this belt of "roots" lies in the northeastern continuation of the "zone of Ivrea" proper and bears the name "zone of Bellinzona" from the town through which the section Fig. 58 is drawn.

[52] Reproduced from Fig. B, Pl. xxxiv, opp. p. 830, of Heim's *Geologie der Schweiz*, Vol. II.

The little-deformed southern zone. The map shows that another belt of crystalline rocks follows south of the "zone of Ivrea." Like the cores of the *decken* farther north, they are of pre-Permian age. But in contrast to them they lack the textural characteristics which the Alpine dynamic metamorphism has imposed on their counterparts farther north. Indeed, only a relatively short distance beyond the southern edge of the "zone of Ivrea," Permian and Triassic formations lie unconformably upon them with gentle dips on the whole, dropping off in flexures and normal faults toward the upper Italian plain (Fig. 58). This southernmost belt constitutes the southern Calcareous Alps and their crystalline basement exposed between them and the "zone of Ivrea" is known as the "Insubrian Alps."

In the southern Calcareous Alps, the folding and mild thrusting is directed toward the south, as Fig. 58 shows. Suess, to whom the strictly unilateral structure of folded mountains was a dogma, spoke of two mountain systems welded together, the Alpine system, overfolded toward the north, and the Dinaric system, overfolded toward the south. This view is proving more and more untenable. The Western Alps constitute one unit. The problem of the largely one-sided overfolding toward the north will occupy us later. Here we are interested in the presence of little-deformed beds on the south side of the Alps, in the rear of an extremely one-sided structure. The south side of the Alps seems to have been uplifted with reference to the upper Italian plain only recently, toward the very end of Alpine movements, probably near the end of Pliocene time.[53] While most of the structure in the Northern and Central Alps was developed, therefore the sedimentary formations on the south side of the Alps lay undisturbed, on a foundation which acted as a rigid body as much as the northern foreland.

6. Résumé

In the Alps we see on perhaps a unique scale the property which may be recognized in all welts, even where the deformation has been as mild as in the Colorado Rockies and the Harz Mountains. It is sufficiently important to be formulated as a law.

Law 23. The structure of welts proves the existence of differential movements in the crystalline cores which approach the nature of

[53] Alb. Heim, *op. cit.*, Vol. II, p. 882.

"plastic" flow. The degree of "plastic" behavior within the crystalline core increases with the depth.

The inner structure of the deformed parts of the crust thus bears out the concept which was introduced early into the train of thought of this book, that the material of the crust reacts to compressive stresses after the manner of "plastic" substances. This concept was developed most forcibly by Argand in his "tectonique de l'Asie."[54] He emphasized that no part of the crust can be called "rigid," or better, "strong" in a physical sense. All crustal deformation is "plastic." The segments between mobile belts are merely less plastic than the geosynclines. Everything we know about crustal movements supports this view. We may formulate it as follows:

Opinion 18. Under compression, the crust yields everywhere essentially by "plastic" deformation.

The word "plastic" in quotation marks, is used in this book without connotations as to the physics and chemistry involved in the process of deformation.[55] It includes purely mechanical deformation as well as all flow accompanied and accomplished by chemical reorganization.

[54] E. Argand, "La Tectonique de l'Asie," *Congr. geol. internat.*, XIII, 1922, *Compt. Rend.*, 1er fasc., e.g., pp. 175-6.

[55] "By the plasticity of a material is meant the property of taking on permanent deformations." Th. Pöschl, *The Physics of Solids and Fluids*, London, 1930, p. 17.

CHAPTER VIII

SPECIAL ASPECTS OF OROGENIC DEFORMATION

"No progress can be made where office speculation is substituted for or given more weight than field studies."
Frank Leverett, in vice-presidential address, 1929.

1. The "Rigid" Foreland Versus the "Plastic" Welt

Opinions. In opinion 15*a* we expressed the conviction that "the rise of crustal folds is due to a compression of the crust." If law 23 is valid it specifies the manner of yielding. It must be essentially "plastic," that is, such as characterizes a "weak" substance. Yet the crystalline substructure which makes up the cores of such welts as we have described is of the same nature as that which forms the crystalline basement of the foreland and is its direct continuation. It is customary to speak of the foreland as being "rigid." Keith, for example, writes of the Appalachian folds: "It is . . . to the presence of the massive basement that the unfolded areas of Canada and New York owe their character, and the basement acting as a buttress received the thrust, protected the overlying sediments, and compelled condensation by folding in the narrow zone of thick sediments just to the east of it."[1]

The Alpine arc is pictured as determined by the buttresses of the Central Plateau of France, of the Vosges, the Black Forest and the Bohemian Forest. Between latitudes 55° and 59° N., the folds of the western Ural Mountains are deflected eastward forming an embayment open toward the west, curving around the plateau of Ufa. Suess says: "The plateau behaves like a fragment of a concealed foreland, against which the outer border of the Urals is dammed back."[2] Wherever there are curves in folded mountain ranges, some "rigid" fragment, visible or hidden from sight, is blamed for the deflection.

Those who interpret crustal dynamics in terms of drifting continental sheets are most emphatic in their emphasis on the controlling

[1] A. Keith, "Outlines of Appalachian Structure," *Bull. Geol. Soc. America,* Vol. 34, 1923, p. 323.

[2] E. Suess, *The Face of the Earth* (trans. by Sollas and Sollas), Vol. III, 1908, p. 365.

influence of such "rigid" older masses. Staub's brilliant discussion of the trend lines of the folded mountains sees everywhere "die kettenzerteilende Kraft dieser alten Massen, die grossartige faltendirigierende Rolle dieser wahren Leitstöcke der jüngeren Ketten."[3]

There can be no doubt that, near the surface, such upwarped regions have acted as obstacles to the "marginal" folding of the sedimentary cover. We shall dwell on this later. But when we speak of the factors that have determined the trend of the mobile belts as such, the distinction of crystalline "rigid" masses outside, from the crystalline cores or welts within, is meaningless. Why should the crystalline pre-Pennsylvanian basement with its coal-bearing Pennsylvanian troughs be intrinsically more "rigid" in the Black Forest, that is, in the northern foreland of the Alps, than in the Aar massif within the Alps, where it has been molded into the remarkable "plastic" folds shown in Figs. 49 and 52? If we have no answer to this question, what shall we say of the twenty, or forty, or perhaps sixty miles of rock below, which form the crust whose deformation is reflected in the welts of the surface? The Archean substructure seems to be as intensely deformed in the Canadian Shield and in the Adirondacks as in the Blue Ridge-Green Mountain axis of the Appalachians. The same is true of the Archean substructure in the foreland and in the folds of any mountain region. The divergent trend of the planes of schistosity characteristic of the crystalline substructure in the foreland is often found to continue in the cores of welts the axes of which strike at an angle to it. With the petrographic and structural identity of the crystalline substructure of foreland and folded mountains so evident in many orogenic belts, there seems to be no concrete basis on which to claim a greater strength for the crystalline substructure of the foreland of rising welts.

On the basis of the "opinions" developed in these lectures, we have no need of any such claims. According to the view here developed, the formation of welts, under compression, is not due to inherent differences in the strength of the crustal materials, but to a *localization of stresses* in and along the furrows, the geosynclines (opinion 16, p. 147).

The larger curves in the pattern of the welts are thus interpreted as prescribed largely by the pattern of the preexisting furrows. As

[3] R. Staub, *Der Bewegungsmechanismus der Erde*, Berlin, 1928, p. 38.

these are thought to result from tension in the earth's crust, it is the behavior of the crust under tensional stresses, not under compression, which determines the major outlines of the pattern of welts.

Now, the reaction of materials to tensional stresses is something quite different from their reaction to compressive stresses. It is instructive to watch the formation of tension cracks in spheres as described in Chapter IV. The slightest irregularities in the glass or paraffin of the spheres cause the lines of fracture to bend abruptly. No one could claim confidently that the fractures are deflected by more "rigid" portions of the glass or paraffin. It is probably not relative "rigidity" at all, or at least not largely, that controls the vagaries of an inhomogeneous substance yielding to tension by breaking or by thinning. "Brittleness," boundary conditions in the heterogeneous materials of the crust, preexisting fracture lines, and other factors enter into tensional yielding in a way totally different from that of compressive yielding. So long as we are unable to specify the physical conditions that produce the curves and kinks in the tension fractures on a sphere in the experiment, we need not dwell on the far more obscure possible causes of deflections in the trend of mobile belts. It is sufficient to recognize the behavior under tensional stress as the real cause for the alignment, first of furrows, then (indirectly) of welts.

Once a tensional phase in crustal deformation has created a mobile belt, the stresses of a compressive phase are localized within and along that zone. What ultimately appears as "foreland" did not escape deformation because beneath the mantle of sediments the crystalline crust consisted of different, more rigid materials, but because in it the crystalline basement stood higher and thus possessed an advantage of position alongside the lower furrow.

The "wedge theory" of Chamberlin. The view here developed pictures the rise of a welt essentially as a differential upward movement of materials in an inhomogeneous, essentially "plastic" crust. It is assumed that only the outermost part of the crust behaves after the fashion of "brittle" substances. Here the differential movements produce tearing, fractures that develop into overthrusts on the margin. This interpretation of folded mountain systems agrees with R. T. Chamberlin's "wedge theory." In his chief paper on this subject,[4]

[4] R. T. Chamberlin, "The Wedge Theory of Diastrophism," *Jour. Geol.,* Vol. 33, 1925, pp. 755-92.

Chamberlin describes the overturning of structural elements, especially the presence of outward thrusts, on both sides of folded mountain systems. He speaks of the "Appalachian wedge," the "Rocky Mountain wedge," the "Caledonian wedge," and so forth.

As far as the Rocky Mountain system is concerned, the brief discussion given above of the structure of such individual units as the Front Range and the Bighorn Mountains, shows that the concept of a wedge applies to individual units rather than to the system as a whole, at least in its northern and central portion. The same is probably true of all mobile belts, at least to a certain degree. Near the surface, the crustal matter forced up by compression must bulge outward. Elastic elongation of the rock materials moved from greater depth to near the surface may add to this outward flaring.[5] In this sense every rising welt may be likened to a wedge. It is even possible that the major zones of thrusting seen at the surface may extend down into the crust as shear planes on one or both sides of a welt. Chamberlin points out that the wedge character of rising systems of folded mountains, as he views them, may be maintained even if no actual planes of shearing develop.[6]

The "orogen" of Kober. Kober pictures the mobile belts as parts of vast compound structures, the "orogens," each consisting of "Randketten" and "Zwischengebirgen."[7] The cordillera of the western United States, for instance, is one such "orogen." Its "Randketten" are the Sierra Nevada and Coast Ranges on the west and the Rocky Mountains on the east.[8] Kober pictures the elements of an "orogen" as essentially coexistent in time and connected by an underlying mechanical principle not further specified. It is evident that in this rigid form his generalization is at variance with all detail of structure and history of our western ranges. The same is true of parts of other mobile belts. It is not a necessary inference anywhere.

But when it is stripped of its implications of a stereotype pattern, Kober's concept of an "orogen" becomes significant. There is unquestionably a tendency for two or more furrows to form within one broader belt ("compound belt," p. 139) with more or less paral-

[5] A. C. Lawson, "Folded Mountains and Isostasy," *Bull. Geol. Soc. America*, Vol. 38, 1927, pp. 270-1.
[6] *op. cit.*, p. 772-3 (Figs. 8-11).
[7] L. Kober, Der Bau der Erde, Berlin, 1921.
[8] *op. cit.*, Fig. 28.

lel trends, either simultaneously or successively, surrounding portions of the crust left undeformed ("Zwischengebirge"). In focusing attention on these relations, Kober has done a real service to geology which will stand whether the concept "orogen" be accepted in its original narrow sense or not. In this discussion, the term "orogen" will not be used, to avoid confusion.

2. The Echelon Structure of Orogenic Belts

In drawing diagrammatic maps, it is customary to represent the axes of the orogenic belts as continuous lines. Upon closer examination, many if not most orogenic belts are found to consist of individual welts lined up in *en échelon* fashion. The continuous lines of our diagrams are justified as marking the *zonal* trend of the welts which by definition runs at an angle to the *individual* trends of the *en échelon* welts. Thus the southern Rocky Mountains as a whole trend from north to south, while the axes of the individual welts run in a north-northwest-south-southeast direction.

The island festoons of eastern Asia offer striking examples. The échelon structure of the island arcs about Japan was described recently in some detail by Tokuda.[9] In Fig. 59[10] one of the maps given by him is reproduced. It illustrates the type of structure observed and its analysis. The map shows the arc of the Riu-Kiu (or Lu-chu) Islands which connect southwestern Japan with Taiwan (or Formosa).

At the northern end of the island arc, along the west coast of Kiushiu, the southernmost of the Japanese islands, seven welts appear lined up *en échelon* (lettered *A-G* on the map). According to Tokuda, some of these welts are "horsts," others are "tilted or folded blocks." At the southern end of the arc, the topography of northern Taiwan and especially the chains of submarine peaks and of islands to the east of it[11] indicate five lines *en échelon* (lettered *L-P*). The chains of islands that connect them, also seem to overlap *en échelon* fashion.

This pattern Tokuda calls "symmetrical échelon structure." Fig. 60[12] illustrates the properties which he distinguishes for the purposes

[9] Sadakazu Tokuda, "On the Echelon Structure of the Japanese Archipelagoes," *Japanese Jour. Geol. Geogr.*, Vol. 5, 1926-1927, pp. 41-76.

[10] Fig. 4-*A*, p. 46, of Tokuda's paper.

[11] See detailed map, Fig. 4-*B*, p. 47, of Tokuda's paper.

[12] Reproduced from Fig. 3, p. 44, of Tokuda's paper.

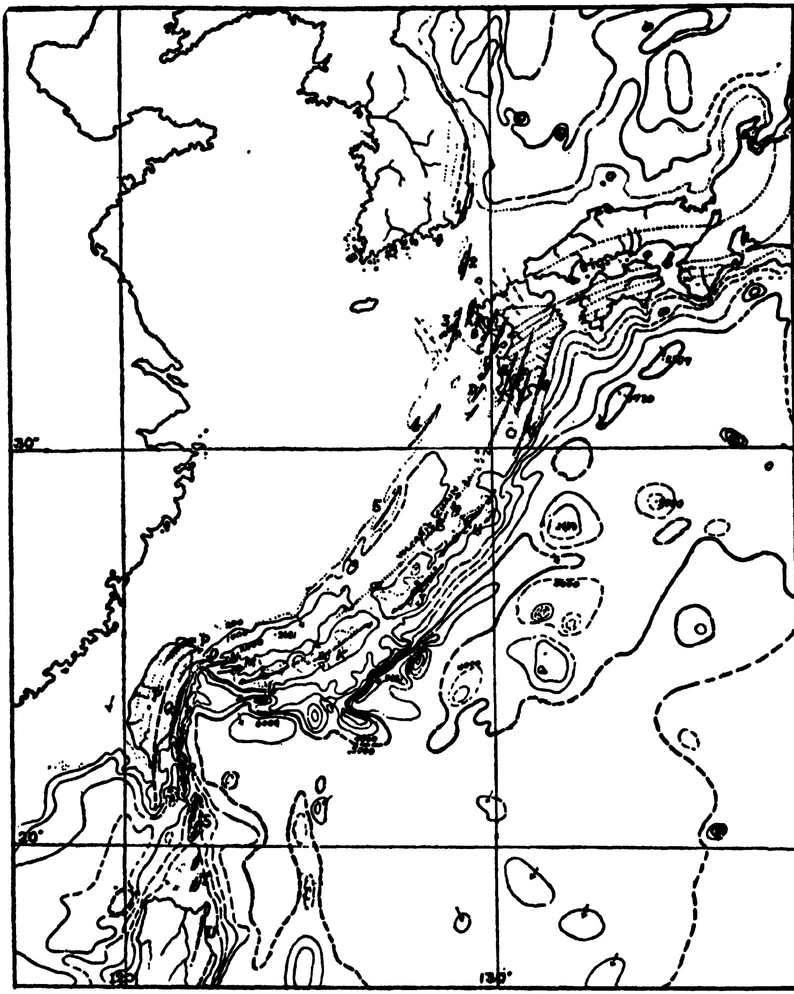
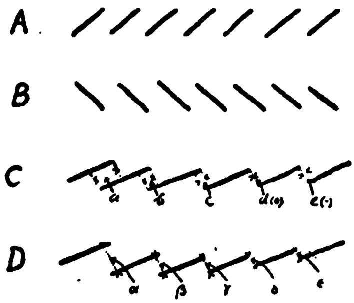


Fig. 59. Tectonic sketch map of the Riu-Kiu Islands, Japan, illustrating the alignment *en échelon* of these island arcs.
(S. Tokuda, 1927)

of precise description. *A* and *B* represent the direction in which the échelon lines or "coulisses" overlap. These two symmetrical types the present writer would designate as "*overlapping toward the right*" (*A*) and "*overlapping toward the left*" (*B*). *C* indicates the degree

to which adjoining coulisses overlap. The significant feature here is the "*spreading*" of the coulisses which in *C* increases from left to right. *D* shows the degree of "*packing*" which increases from left to right. In order to complete the description the angle by which the



Diagrammatic explanation of various types of échelon arrangement.

A......*m*-shaped échelon arrangement.
B......w-shaped " "
C......a>b>c>......
D......α>β>γ>......

Fig. 60. Diagrams to illustrate the different ways in which the units are arranged *en échelon* in island arcs.

A = units *overlapping toward the right*; *B* = units *overlapping toward the left*; *C* = *spreading* of the units ("*coulisses*") increasing from left to right; *D* = *degree of packing* increasing from left to right.

(S. Tokuda, 1927)

coulisses are deflected from the axial line of the échelon belt should be indicated. It may simply be called the "*deflection.*"

Using these terms, we can describe the Riu-Kiu arc as consisting of lines of topographic elevations arranged *en échelon,* overlapping toward the left on the left side of the arc and toward the right on the right side, with packing and spreading increasing on the whole toward the center of the arc and with the deflection decreasing from about 30° on the sides to zero in the middle.

This same pattern is shown even more strikingly in the arc of the Kurile Islands.[18] It shows specific properties which should lead to a definite understanding of its mechanical causes.

Tokuda showed that this pattern can easily be produced when "a thin sheet of plastic paper coated with a thin layer of rice paste" is laid on a glass plate and then is pushed forward here and there with a finger. The reader is referred to the original paper for thirty photographs of wrinkles produced in this manner and their similarity to patterns well known in orogenic zones.

[18] Figs. 1 and 2, p. 43, of Tokuda's paper.

What is it, that Tokuda has demonstrated? The portion of the paper covered by the finger is prevented from wrinkling by the pressure of the finger. Its outline is that of the finger, roughly semicircular in the direction of the movement. This "rigid" plate is moved bodily in one direction. This means that on all sides except in the direction of movement rotational stresses are set up. Given such an arrangement, the rise of *en échelon* folds of the type described above seems inevitable.

The question is only: why should any curved segment of the earth's surface behave as if it were more rigid than the rest? This is the same problem of "rigid" masses that was discussed in the preceding pages. The answer given there seems to satisfy this question also. Under tension, curved fractures showing all the patterns familiar in orogenic zones, form readily (p. 89). It is thought that the *en échelon* welts of the island festoons arose secondarily like all welts, under compression, from primary arcuate furrows, formed under conditions of tension in the crust. Here, as everywhere, the yielding which produced the welts was limited largely to the furrows.

It is even possible that the *en échelon* pattern itself arose directly and primarily through the action of the tensile stresses. In that case, compression would be responsible only (or largely) for the crustal relief, not for the pattern of these island arcs, in the manner described later for such orogenic belts as the Coast Ranges of California (Chapter x).

3. "Underthrust" Versus "Overthrust"

Something remains to be said about "underthrust" and "overthrust." These terms obviously have a meaning only when tied logically to displacement with reference to a fixed horizontal system of coordinates. The block on one side of an inclined fracture (or axial plane of a fold) is thought to be at rest relative to the coordinates of reference; the other moves. When the upper one moves, the resulting displacement is called an overthrust. In the opposite case, we speak of an underthrust.

In the compression box used in most experiments on folding since James Hall (1812),[14] the solid floor of the box furnishes the lines of

[14] Published in *Trans. Roy. Soc. Edinburgh,* Vol. 7, 1815, pp. 79-108, Figs. 1-5 (quoted from W. Paulcke, *Das Experiment in der Geologie,* Berlin, 1912, p. 7, Fig. 3).

reference. In the case of crustal deformation, it is necessary to refer movements to an imaginary sphere of reference below the crust. If we picture the major orogenic epochs as times of world-wide compressive stresses, we may think of these stresses as due to the crust having grown too large for the shrinking subcrustal body of the earth. In a crude way, we may compare the condition along one meridian to fitting a hoop about a sphere of smaller diameter. If the material of the hoop is brittle, it may break at one point as we force it onto a sphere of smaller circumference. We can fit the fractured hoop in three ways:

(1) We may fasten the hoop against the sphere at a point diametrically opposite the point of fracture. In that case both free ends of the hoop move with reference to the surface of the sphere.

(2) We may press one free end of the hoop against the sphere, allowing the other to ride over it.

(3) We may take pains to hold one free end at a fixed position above the sphere, allowing the other to slide under it.

According to our definitions, the last case is an underthrust, the second an overthrust, and the first a combination of the two. For the larger aspects of orogeny, the simple underthrust (3) seems improbable. Something corresponding to (2) has been in the minds of most workers of the past who spoke exclusively of overthrusts. The first case involves least lateral displacement and would seem the most probable. It would have to be called simultaneous over- and underthrusting.

In view of the "plastic" behavior of the crust expressed in law 23 (p. 199) and opinion 18 (p. 200), we must think of the hoop yielding "plastically" at its weakest point rather than by fracturing. There would be no essential fracture but rather a zone in which the hoop would be forced outward by thickening. The parts of the hoop nearest the zone of yielding move closer together. In that sense, the welt may be said to be forced upward by underthrusting. Near the surface fractures would form. Along these fractures, the material of the welt, urged on by the rising central portion, would be thrust forward actively over an inert foreland. It is probable that, measured in miles of actual displacement, the active "overthrusting" exceeds the "underthrusting" of the crust below.

Coupled with this concept of the essentially plastic character of all crustal deformation (opinion 18, p. 200), the use of the term "underthrusting" is widely different from that which might be called the "classical" meaning of the term. Lawson has given a graphic description of the way the principal fracture is pictured in the "classical" view of underthrusting. It starts at the top of the crust and grows downward. "The rupture would be concave downward, and under this concave fault the underthrust would proceed slowly, culminating in the down plunge of the stub end of the crust into the zone of flowage."[15] In this picture the overriding block is rigid and passive, corresponding to the last of the three cases discussed above. The details of welt structure, as described in the preceding chapter, seem to be at variance with this view.

4. Orogenesis and the Geometrical Aspects of Crustal Shortening

The Problem. In the paper quoted above, Lawson introduces the idea, that in the rise of welts a part of the crust is lost in the subcrustal "zone of flowage." On this he dwells emphatically. "The unanswerable argument for underthrusting as the primary mechanism in crustal shortening is that there is no other imaginable way in which the crust can be shortened, to the extent shown in the Rockies, the Appalachians, and other ranges, except by the down plunge of a portion of the crust and its absorption in the subcrustal region" (*op. cit.*).

This important statement is evidently independent of the particular form in which Lawson has pictured underthrusting. It applies with equal force to our view. If the formation of welts is the result of stresses affecting the earth's crust as a whole, there must be an actual shortening of the crust. This means that material must have been removed from the crust across its whole thickness, from top to bottom. In any cross-section of a mobile belt, the dimensions of the material that must have been forced out under compression are given by the thickness of the crust and the amount of actual shortening it has suffered.[16] From the nature of the rocks exposed in even the most

[15] A. C. Lawson, "Folded Mountains and Isostasy," *Bull. Geol. Soc. America*, Vol. 38, 1927, p. 264.

[16] This latter value must not be confused with the shortening of surface sediments as displayed in the pattern of folds.

intensely deformed welts such as the Alps, it seems evident to the writer that no such quantities of deeper crustal materials have reached the surface as one would expect, if in the process of shortening all the material had been forced from the crust out onto the earth's surface.[17]

This finding is of such importance that it deserves being phrased in the form of a law.

Law 24. The volume of the matter forced out upon the surface during an orogenic epoch is only a small fraction of the matter that had to be eliminated in order to shorten a hypothetical crust several tens of miles thick to the extent indicated by the folding of the rocks near the surface.[18]

This law leaves room for but two alternatives: Either the transfer of matter is limited to the very few miles of the outermost crust we actually see involved in orogenic movements; or much of the crustal matter that is removed when the crust shrinks is expelled downward into subcrustal space.

The first alternative has been chosen by those who think in terms of drifting continents. In their view, the transfer of crustal matter consists in a wrinkling of the lighter portions of the outer skin of the earth driven by forces which remain to be understood. If the observable properties of the outer crust lead inevitably or at least with great probability to the assumption of such drifting the geologist is justified in leaving to the geophysicist the search for a physical explanation of such movements. In the earlier part of this book the writer has shown that, so far as his present knowledge goes, the assumption of surficial drifting is not only not necessary but incompatible with essential facts.[19]

This leaves only the second alternative, that the shortening of the crust's circumference is accomplished by forcing a large amount of crustal material downward into subcrustal space. But how can that be accomplished while all subcrustal space is occupied by rock materials under high pressure?

Elimination of crustal materials under compression. At first sight this suggestion seems almost absurd. Yet a little reflection will show

[17] See, e.g., Otto Ampferer, "Geometrische Erwägungen über den Bau der Alpen," *Mitt. Geol. Ges. Wien,* Vol. 12, 1920, p. 149.

[18] See definition of crust, pp. 37 and 43.

[19] See esp. pp. 41 and 76.

that on the contrary it follows inevitably from the very concept of world-wide crustal stresses (opinions 13, p. 114, and 15, p. 141). For the purposes of analysis, let us treat the simultaneous processes of subcrustal shrinkage and crustal adjustment as taking place in separate steps. The subcrustal body of the earth is to shrink first, then the crust is to be adjusted to the smaller surface. Suppose the radius of the earth were decreased by one mile. Let r stand for the radius of the subcrustal earth, that is, from the center to the bottom of the crust as defined in the chapter on isostasy. Then the space between the crustal and the subcrustal body of the earth that would form if the two processes took place separately is

$$\frac{4}{3}\pi r^3 - \frac{4}{3}\pi(r-1)^3 \text{ cubic miles, or}$$

$$4\pi r^2 - 4\pi r + \frac{4}{3}\pi \text{ cubic miles.}$$

The mean radius of the earth is about 3,957 miles (6,368 kilometers). Since there is reason to believe that the crust may be as thick as 60 miles, we may take $r = 3{,}900$ miles. This gives a volume of about

191,081,000 cubic miles

for the void created below the crust by a reduction of the radius by one mile.

At the same time, the surface of the subcrustal earth would be reduced

$$4\pi r^2 - 4\pi(r-1)^2 \text{ square miles, or}$$
$$8\pi r - 4\pi \text{ square miles.}$$

If we limit this reduction of area to two belts of the length of two great circles, each 25,000 miles long, each belt would be narrowed by about 2 miles. To produce this reduction of surface the body of rock 50,000 miles long, 2 miles wide, and, say, 60 miles thick must be forced out from the crust, that is,

6,000,000 cubic miles.

Compare these 6,000,000 cubic miles with the 191,000,000 of the space created by a shrinkage of 1 mile. But don't be deceived by the discrepancy. The 191,000,000 cubic miles of space are made to vanish not so much by filling up with material forced from the

crust as by the reduction in the area of the surface which follows the shortening of the crust. What these figures do indicate is that a negative pressure gradient exists downward in a crust which has to adjust itself to a shrinking subcrustal core provided it possesses some residual strength. Here the full significance of the definition of the crust becomes apparent which we developed in our discussion of isostasy and embodied in opinion 4 (p. 39). The term "residual strength" refers to the property of a weak material to resist further deformation so long as the pressure acting on it remains constant. The law of isostasy (law 9) shows that below a certain depth the crustal materials, under cubical compression and rather high temperatures, are practically devoid of strength,[20] that is, they are capable of infinite deformation under constant pressure. This is one of the properties of liquids.

The very concept of the crust, then, rests on the property of residual strength. We have shown that, given that property, any shrinkage of the subcrustal body of the earth must result in a negative pressure gradient downward within the crust. This causes the crust to yield at its weakest points by deforming at right angles to its surface. Since the negative pressure gradient is directed downward and coincides with the direction of gravity, the larger part of the crustal materials is forced downward. Only the outermost, least "plastic" part of the crust yields upward, rising in the form of crustal folds which we have called "welts." They register the shortening of the surface of the crust. The larger part of the vertical elongation of the crustal column beneath a welt would extend downward into subcrustal space as "roots of the mountains" if that were not the realm where by definition residual strength vanishes. Instead of forming a "root," the lower portion of the lengthening crustal column loses its identity as part of the column so far as crustal dynamics are concerned.[21] This corresponds to what Lawson has called "the

[20] The reader should be careful to remember that the term "zero strength" implies nothing concerning the molecular state of the crustal materials. It has nothing to do with such concepts as "molten" and "crystalline," or "homogeneous" and "inhomogeneous." It is also entirely independent of the quantitative value of the unbalanced force required to produce deformation, that is, the "coefficient of internal friction."

[21] This does not mean, of course, that it would be melted or need lose all structural differentiation. Anyone who has watched the pulling of candy knows how enormously a structural pattern of varicolored strands of candy can be deformed without losing the characteristics of the pattern.

down plunge of a portion of the crust and its absorption in the subcrustal region."

Opinion 19. Under compression, the reduction or "shortening" of the crust is accomplished by a downward expulsion of crustal matter into subcrustal space, largely along mobile belts. Only in the uppermost part is there an upward movement which leads to folding and piling up of thrust sheets.

This reasoning implies that while the crust is under compression there must exist a level, a relatively short distance below the earth's surface, above which all deformation is upwards and below which deformation is directed downward. This is the "level of no strain" of the geophysicists which tentative computations indicate as lying but a few miles below sea level. As the crust thickens downward below this "level of no strain" along a mobile belt, the upper part of the crust is pushed together. For this reason experiments such as those recently published by Hans Cloos[22] are entirely valid, in which a yielding layer of some more or less plastic material is deformed by the pushing together of two movable plates of sheet iron, across which the material was spread.

Isostatic consequences. From the view expressed in opinion 19, the isostatic behavior of the welts follows as a corollary. We must remember that our definition of the crust is purely physical. It is entirely independent of the chemical and petrographic character of the crustal materials. If it is true that the crust beneath the Pacific Ocean lacks all acid rock materials and consists of heavy rocks even at the surface, the length of a column of unit area down to the base of the crust where all residual strength vanishes, is, of course, less than in the center of a continent, where light rocks may be very thick. For the weight of a crustal column of unit area tends to be the same everywhere. That is the essence of the law of isostasy.

All geologists agree that even within the crust, that is, in the small thickness of something like sixty miles, there is a tangible increase in the density of crustal materials from the surface downward with the granitic portion forming only a small upper fraction. Whether the increase is discontinuous or continuous, is irrelevant for this discussion. The essential point is that when crustal shortening takes place the piling of the surficial part into crustal folds or thrust sheets is

[22] See p. 145 of this book, esp. Figs. 33 and 34.

accompanied by a downward thickening of the acid portion of the crust and a corresponding downward expulsion of the heavy end of the thickening column. As the crustal column beneath a welt grows longer in a vertical direction the larger, heavier basal part ceases to act as a part of the column, becoming one with the "plastic" asthenosphere. This means that a larger part of the materials from the surface to the depth where all strength vanishes consists of light materials. The compression which produces the mountains thus increases the proportion of lighter to heavier crustal materials which makes it possible for the mountains to stand up high when isostatic adjustment takes place. The relation is automatic and inevitable.

Dr. Meinesz' gravity studies in the Netherlands East Indies[23] have produced results which are of greatest interest in this connection. He found abnormally large isostatic anomalies from which he concludes that "apparently isostasy is not maintained where tectonic activity takes place. . . . This was not unexpected as isostasy means floating equilibrium of the earth's crust and the presence of tectonic forces may be expected to disturb the equilibrium."[24]

The largest anomalies are negative and line up in such a way as to form a narrow strip, almost one hundred miles wide, which runs through the whole archipelago and is bordered on both sides by regions of positive anomalies. "On the average the difference between the negative anomaly of the strip and the neighboring positive anomaly is about 150 to 200 millidynes but locally it attains greater values; west of Halmaheira this difference amounts even to 430 millidynes."[25]

The location of this strip is indicated in a diagrammatic way in Fig. 61.[26] "West of Sumatra it runs either over the islands or between the islands and the coast. South of Java it coincides with the submarine ridge between the two deeps running parallel to Java in the Indian Ocean, further to the eastward the strip coincides with the row of islands: Timor, Tenimber Islands, Key Islands, Ceram, but

[23] F. A. Vening Meinesz, "Maritime Gravity Survey in the Netherlands East Indies; Tentative Interpretation of the Provisional Results," *Proc. Kon. Akad. Wetensch.*, Amsterdam, Vol. 33, 1930, pp. 566-77. Quotations below refer to this paper. See also F. V. Meinesz, "Gravity Anomalies in the East Indian Archipelago," *Geog. Jour.*, Vol. 77, 1931, pp. 323-49.

[24] *op. cit.*, p. 568.

[25] *op. cit.*, p. 569.

[26] For details see the maps accompanying the papers quoted above.

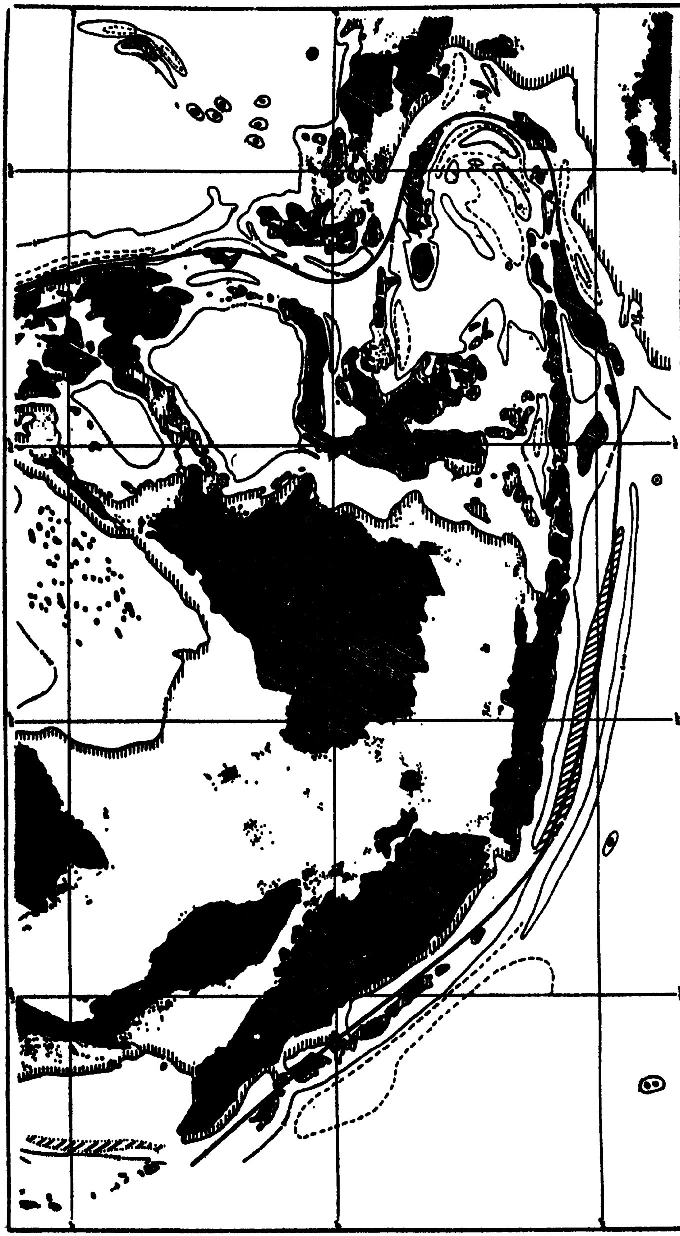


Fig. 61. Map of the Netherlands East Indies to show the relation of the axis of exceptionally large negative gravity anomalies to islands and deep-sea furrows.

Contour lines: —200 meters; —3,000 meters; —6,000 meters.
Hachured = edge of shelf (—200 meters).
Widely spaced ruling = submerged welts.

(Drawn from Meinesz, 1930)

from here it leaves the row and takes a northward course west of the island of Halmaheira over the Taland Islands towards the Philippine Deep."

This course of the strip of negative anomalies is quite unexpected in "that the deviations of isostasy do not show a clear parallelism with the topography of the earth's crust; they appear to be remarkably independent of it."[27] This lack of correlation with the topography and the magnitude of the anomalies prove conclusively that these anomalies are not due to a defective isostatic reduction. They must represent "real deviations of the equilibrium of the earth's crust."

Basing his reasoning primarily on the gravity data, Meinesz arrives at this conclusion: "Carefully examining the matter it appears more plausible to assume that the strip of negative anomalies is caused by some abnormal accumulation of light surface material in a subsurface denser layer. This brings us to the hypothesis which in the opinion of the writer covers all the facts, that the cause is a downward folding of the whole earth's crust with the exception of a thin surface layer.

"This surface layer folds upwards and in the long run forms overthrust sheets in the manner as has been stated by the geologists in the Alps and in other folded mountain systems. Its thickness is estimated at not more than a few kilometers while the main part of the [acid portion of the] earth's crust is thought to have a thickness of some twenty kilometers or more.

"The downfolding of this main part brings about the accumulation of light surface material in the crust which corresponds to the strip of negative anomalies.

"This hypothesis is in harmony with the supposition of Molengraaff, Brouwer, and numerous other geologists that the Indian Archipelago represents the first stage of a mountain folding process.

"The only important point in which this hypothesis differs from the actual range of ideas, is the fact that this main (downward) folding process has a less local character than the superficial folding of the upper layer. This appears to act more or less independently and often shows many parallel folds accompanying one downward fold, as for instance in the double Banda arc. In this way not every

[27] *op. cit.*, p. 568.

surface fold is accompanied below by a downward fold, while the prevalent view is that every fold develops its isostatic compensation exactly below it. Now, apart from the fact that the gravity results in the archipelago show that isostasy is not valid during the process, the hypothesis which is mentioned here, seems a reasonable one. The downward folding main part of the earth's crust is many times thicker than the surface layer and may therefore not be expected to undergo the same local foldings. Probably also this downward folding will not assume the same shape and overthrust or underthrust character as the surface folds."[28]

At one point in the preceding quotation the present writer has inserted four words in brackets, all that were needed to change Meinesz' account from the Airy hypothesis to that adopted in this book. Following current usage, Meinesz, like Airy, considers the acid shell of the earth as identical with the crust. In this book the "crust" is defined as that outermost portion of the body of the earth within which the rock materials, whatever they happen to be, on the whole possess sufficient strength to transmit stresses.

This slight change makes Meinesz' hypothesis practically identical with that developed by the writer on purely geological grounds. This convergence of views derived from independent sets of data strengthens the promise of their usefulness.

Meinesz' discovery is of fundamental importance and is sufficiently proved to deserve being set down as a law.

Law 25 a. Within some of the mobile belts that have been active since the beginning of Cenozoic time, unusually high negative gravity anomalies exist, aligned in such a way as to form relatively narrow and long zones.

Law 25 b. On the whole, these zones coincide neither with the axes of furrows nor of welts but take such a course that they now follow one, then the other, and again pursue an independent course.

Two opinions derived from Meinesz' work deserve being formulated specifically:

Opinion 20 a. Long, narrow strips of excessively high negative gravity anomalies represent axes of mobile belts along which active downward thickening of the crust is now in progress.

[28] *op. cit.*, pp. 570-1.

Opinion 20b. They indicate that the dominant downward movement of matter within a mobile belt undergoing active compression prevents isostatic adjustment while compression lasts.

Opinion 20*b* agrees entirely with the fact long recognized by geologists that in all mobile belts vertical upward movements have assumed large proportions only after most of the folding and thrusting incident to crustal shortening under compression had been accomplished.

Meinesz extends his hypothesis to include the narrow deeps which locally border rising welts. He writes: "If the downward folding is not completely covered up by the surface folds, the downward movement of the earth's crust reveals itself by an ocean deep, as in this instance the Philippine Deep or the Java Deep. Probably the sea-side slope of these deeps may be regarded as a true image of the sloping of the earth's crust towards the downward fold, which is situated itself below the ridge bordering the deep on the land side. This agrees with the situation of the strip of negative anomalies."[29]

This part of Meinesz' hypothesis may well apply to some of the modern deeps or at least parts of them. But it cannot be extended to geosynclinal furrows. Basic intrusions, often extremely basic, occur so frequently (law 28*a*) in the geosynclinal sedimentary series laid down in furrows identical with "deeps" in shape and in the depth to which their floors were depressed, that the method by which they were formed must make possible the introduction of such basic materials from below. This is impossible if the "deep" marks the line along which the acid portion of the crust is thickening.

This objection has great weight in the writer's mind because he has been led by a number of independent facts to accept the dual hypothesis concerning the mechanism of diastrophism, in which the close association of welts and furrows follows automatically without special assumptions.[30]

Addition of crustal materials under tension. In order to be acceptable, this interpretation of the isostatic behavior of welts must be applicable to furrows when compression is replaced by tension. Let us turn, for the moment, from welts to furrows. We apply the same reasoning as before. When the radius of the subcrustal body of the

[29] *op. cit.*, pp. 571-2.
[30] See pp. 139-47.

earth is increased by 1 mile, from $r - 1$ miles to r miles, the surface at the base of the crust is enlarged by 98,000 square miles. If we limit this increase of area to two belts of the length of two great circles, each 25,000 miles long, each belt would be stretched to the extent of about 2 miles. This stretching would result, of course, in a reduction of the thickness of the crust. This would cause the surface to be lowered to form a furrow.

In order to get a crude idea of the depth of a furrow produced by this stretching alone, we may assume that the volume of the mobile zone involved in the change of shape remains constant. Since we are here concerned with permanent changes beyond the elastic limit this assumption is justified. We have no means by which we could evaluate the changes in the materials at greater depths of the crust due to the pressure changes involved in the "plastic" deformation of the crust which we assume here. They are almost certainly, however, of a sufficiently smaller order of magnitude that we may neglect them here just as we did before implicitly in the discussion of a thickening of the crust beneath the mobile belts.

For our purposes here it is sufficient to deal only with a section at right angles to a mobile belt. In any rectangular portion of such a section, the relations between the horizontal and vertical dimensions may be expressed as follows:

$$wx = a\ (t - x)$$

$$\text{or,} \quad x = \frac{at}{w + a},$$

where t equals the original thickness; w, the original width; x, the decrease in thickness; a, the increase in width. In other words, if a zone 200 miles wide on a crust 60 miles thick is stretched by 2 miles, the thickness is reduced by 0.59 miles. If the crust were only 30 miles thick, the reduction would be only 0.3 miles. Or if the stretching of 2 miles were limited to a zone of only 60 miles width on a crust 60 miles thick, the surface would drop 1.9 miles.

That rock materials should behave like ductile materials, such as steel[31] below a load of ten or twenty miles may seem plausible enough. But the picture of rocks such as we know them at the surface,

[31] See p. 142.

stretching under tension, is so contrary to our experience that at first sight it seems unreasonable.

Yet the geologist who affirms, with good reason, that only a very few thousand feet of sediments can have existed on top of the anticlines in the anthracite fields of Pennsylvania or on those of the Jura Mountains of Switzerland, must assume some stretching on the outer parts of each anticline much as is assumed here. Unquestionably, the outermost part of these anticlines was greatly fractured by closely spaced joints as folding progressed. Why should not a horizontal land surface react in the same way as tension progresses? Ten cracks, each one millimeter wide, distributed over a distance of one meter, would account for a lengthening by 1 per cent. And this amount of stretching would be accomplished within, say, one hundred thousand or two hundred thousand years.[32] We are apt to overlook the slow rate at which the tension is applied. We cannot be certain, in fact, that at that rate even our most brittle rocks would fracture at all except perhaps at the very surface.

Let us suppose that they fracture, in the outermost part of the crust. At and near the surface, the abnormally large number of joints would influence the rate of weathering and of erosion on the tensionally stressed surfaces, as soon as the joints came into existence as capillary cracks. It may be that this is the reason why all but the most recent anticlinal areas, in which tensional stresses arise through the bulging of the surface, form topographic basins. In that case the lowland center of such a structure as the Cincinnati anticline, for instance, would be the product of differential erosion which progressed simultaneously over the whole area, with the erosion escarpments on its circumference marking essentially the boundary of the less fractured lower slopes of the anticline.[33]

Similarly, crustal belts yielding under tension might be expected to suffer erosion faster than more normal parts of the crust, which would hasten the time when the sea would gain access to them.

Below a load of a few hundred feet of rock, under the combined action of the pressure from above and the horizontal regional tension,

[32] The question as to what constitutes a "short episode" in diastrophism will be discussed systematically in Chap. XII, pp. 393-402.

[33] Under this assumption the rate of recession of the cliffs would not be a measure of the time involved in the formation of the topographic basin.

fracturing would take place along planes of shearing only. All joints would be inclined. There would be no open joints, if, indeed, fracturing would take place at all.

To the writer this picture of a crustal belt under tension seems reasonable. He believes, however, that only a part of the lowering of the surface along a deepening furrow is a direct result of the tensional stress. The larger part of the sinking is thought to result from the introduction into the crust of heavy basic material from the subcrustal region, in the form of basic intrusions. This was indicated briefly in the discussion of Washington's law (p. 44) and will be further elaborated in the chapter on intrusives (pp. 268-73).

In this chapter, discussion is limited to the direct effect of tension in order to outline clearly the nature of the process.

Isostatic consequences. The reductions in the thickness of the crust due to tension alone, as pictured above, do not represent the amount to which the earth's surface could actually be lowered. The condition of isostatic equilibrium at the base of the crust is disturbed when one column becomes lighter. This creates an upward force which lifts the column by introducing beneath it as much subcrustal material as is required to make its weight equal to that of all other crustal columns. But since the subcrustal material is heavier than that of the upper parts of the crust, the uplift is less than the lowering produced by the stretching. Suppose stretching alone would lower the surface by one mile. If the average density of the crust is 3.0 and that of the subcrustal material near the base of the crust is 3.3, then a column nine-tenths of a mile of subcrustal material would have to be added to the base of the stretched column to restore equilibrium.[34] That would leave a difference of one-tenth of a mile. To such an amount the surface of the stretched belt would actually be lowered.[35]

This is the exact reverse of the process here pictured as being involved in the formation of a welt. In both cases we have left out of consideration the subsidiary effects of deposition and erosion. They must become factors in the deformation of the crust as soon as the vertical stresses introduced by them cause the total vertical stress to exceed the strength of the crust (see p. 39). Sediments of thickness

[34] See also the discussion of the same relation on page 59.

[35] No value attaches, of course, to the figures themselves. They are used merely in a qualitative sense, to illustrate the nature of the process involved.

and areal extent sufficient to affect the isostatic balance of the crust require furrows (or basins) for their accumulation. After the furrow has come into existence, the load of sediments it receives depresses it further. On page 60 we have seen that the effect of the sediments alone is limited. Here we recognize it as a factor in the development of a geosyncline.

Correspondingly, erosion attacks regions that have been uplifted. It creates stresses which cause a further rise of the surface which is added to the upward movement due to compression alone. In this way the interaction of the atmosphere with the surface of the earth accentuates the changes wrought by the primary crustal stresses.

Before passing on to further comments on the origin of welts and furrows, we shall formulate the ideas developed in the last pages.

Opinion 21. Under tension, the enlargement or "lengthening" of the crust is accomplished by an upward introduction of subcrustal materials into the crust largely along the mobile belts. Only in the uppermost part is there a downward movement of the crust. This forms the furrows.

Opinion 22. The isostatic condition of the crust is the result of the addition or subtraction of heavy materials near its base.

5. The Amount of Crustal Shortening

The Southern Rocky Mountains. If the opinions formulated above are to hold good, they must be in reasonable agreement with the dimensions of the actual reductions and enlargements recorded in the surface structures. Unfortunately, for the time being at least, it seems impossible to arrive at reliable figures for either change.

The record of surface reduction preserved in the rock folds is more accessible than that of surface enlargement which lies buried beneath the thick sediments of geosynclines. But even where the structure of a welt is freely exposed, so much of it has been eroded away at the top and lies invisible beneath the surface, that unbiased measurements of the actual shortening are impossible. This is true even in regions of relatively simple structure. R. T. Chamberlin's careful study of the section across the Front Range from Lyons to Glenwood Springs illustrates this point. His reconstruction of the

sedimentary cover[36] assumes essential conformity of all formations and is dominated everywhere by open folds and normal faults. The results of detailed work at many points in the Front Range have shown that this interpretation is not justified. The western part of his section, for instance, crosses the Williams Range thrust fault with a westward thrust of four miles, recently discovered by Lovering. This makes it probable that the shortening of only eight miles[37] computed by Chamberlin is too small. Yet no one can tell how much too small this estimate is. Lee thought that the structure of the southern Rockies could be understood in terms of vertical displacements only, with no significant shortening.[38]

Shepard, on the other hand, crossing the southern Sangre de Cristo Range, where the Rocky Mountain system has tapered down to a single range, was greatly impressed with the sharp folding of the sedimentary mantle which is here largely preserved. He estimated that a section near Mt. Trinchera, ten miles long, has been reduced by 37 per cent of its length.[39] Thinking in terms of percentages he reasoned that for the much longer Lyons-Glenwood Springs section R. T. Chamberlin's estimate must be too low. In his answer, Chamberlin pointed out that thinking in terms of percentages is of little value in the discussion of crustal shortening. After all, the actual shortening inferred along the Mt. Trinchera section only amounts to three miles.[40]

This discussion is quoted here only to show the uncertainty of such estimates even where the structure is quite simple. After all, the amount of shortening in the southern Rockies appears to be small, measurable in tens of miles.

The Western Alps. It is the estimates that have lately been made of the crustal shortening in the Alps and mountains of Alpine structure in general that bear on the validity of the opinions formulated above.

[36] R. T. Chamberlin, "The Building of the Colorado Rockies," Part II, *Jour. Geol.*, Vol. 27, 1919, pp. 225-51, Figs. 5-11.

[37] From an original length of 140 miles to 132 miles.

[38] W. T. Lee, "Building of the Southern Rocky Mountains," *Bull. Geol. Soc. America*, Vol. 34, 1923, pp. 285-300.

[39] F. P. Shepard, "Indications of Important Horizontal Compression in the Colorado Rockies," *Am. Jour. Sci.*, Vol. 5, 1923, pp. 403-8.

[40] R. T. Chamberlin, "On the Crustal Shortening of the Colorado Rockies," *Am. Jour. Sci.*, Vol. 6, 1923, pp. 215-21.

Lachmann, for instance, estimating offhand in round figures, arrived at "not less than 1,660 kilometers" as the probable shortening in the Alps.[41] "We are justified, without doubt," he writes, "to draw from the *decken* theory in its present form the conclusion that the Dinarides[42] lay in the region of the present Sahara before the Alpine folding."

The most extreme view was expressed by Kober. In his book, *Der Bau der Erde*, he maintains that the sediments of the typical geosynclines, the Tethys, for instance, represent not the deposits of relatively narrow troughs but of true oceans of dimensions comparable to the Atlantic Ocean,[43] each "ein offenes Weltmeer." Kober takes the average width (1,000 kilometers) of what he calls the Mediterranean "orogen," e.g., the belt from the northern edge of the Alps to the southern border of the Atlas Mountains, and applies to it the ratio of shortening 1:2-3. This does give an original width of 2,000-3,000 kilometers which is indeed comparable to that of the Atlantic between Europe and North America.[44] But the larger part of the 1,000 kilometers is occupied by what he calls the "Zwischengebirge." The writer knows of no observations that would justify extending the ratio of shortening to the whole width of the orogen. Few geologists would probably accept this basis of an estimate. But the tendency to think that the intricacies of Alpine structure "prove" a shortening that may lie nearer 1,000 kilometers than 100 kilometers is evident in many places in European literature. In fact, it is safe to say that Wegener's theory appealed so strongly to Swiss, French, and Dutch geologists because it gives unlimited possibilities for what seem excessive amounts of shortening along the whole Alpine system, from Morocco to the Dutch East Indies.

Yet the men who are most intimately acquainted with the *decken* structure of the Alps are well aware of the deceptive character of the structural details. Heim has listed the factors which must be taken into account before one can make an attempt to estimate the short-

[41] R. Lachmann, "Ueber den Bau alpiner Gebirge," *Zeitschr. Deutsch. Geol. Ges., Monatsberichte,* Vol. 65, 1913, p. 159.

[42] The Insubrian belt of our sketch of Alpine structure on p. 199; i.e., the region south of the Pennine Alps.

[43] L. Kober, *Der Bau der Erde,* Berlin, 1921, p. 143. "In Wirklichkeit sind die Geosynklinalen grosse Meeresräume, echte Ozeane," p. 45.

[44] *op. cit.,* p. 158.

ening of an Alpine system of folds and thrusts.[45] (1) Parts of higher *decken* may have been transported passively on the back of the moving support. (2) The stratigraphic units which form one thrust mass may have been torn or sheared off their base by the pressure of higher thrust masses. The distance between the separated ends of the torn-off mass and its support in such cases, cannot be counted as shortening. (3) One must not confuse the distance over which a thrust plane can be traced with the extent of the movement actually accomplished on that plane. An actual movement of a few hundred feet may be traceable over a thrust plane for a distance of tens of miles.[46] (4) All "plastic" deformation is connected with a thickening and thinning of the rock units involved. Wherever stretching has occurred which reduced the stratigraphic units of a folded series to $1/x$ their original thickness, the apparent shortening derived from the surface of the fold must be corrected by the coefficient $1/x$. In this, x may vary from 10 to 50, perhaps even to 100. Argand has likened the movement of the Pennine *decken* to the squeezing of paste from the narrow opening of a tube. The wide stretch of their folds reflects the inner movements of a plastic mass deformed at depth. The horizontal extent of these movements is surely far in excess of the actual displacement of the crust required to produce them.[47]

This is a crucial point which has a profound effect on all reasoning concerning crustal shortening. Let us view it in the simplest manner possible. Take a transverse section of the upper part of the crust in a mobile belt. Assume its dimension parallel to the strike to remain constant while it is shortened at right angles to the strike and lengthened upwards. Since one dimension is assumed to remain unaltered, we need only consider the area of the cross-section. Let this section be square before compression. If the crustal part affected by this deformation be 10 miles thick, let the section be 10 miles wide at right angles to the strike. Since the deformation is to be "plastic," the

[45] Alb. Heim, *Geologie der Schweiz*, Vol. II, pp. 49-50. (Not quoted literally nor in the order of the original.)

[46] For a noteworthy special case of a "tectonic" unconformity which is of interest in this connection, see T. V. Nolan, "Notes on the Stratigraphy and Structure of the Northwest Portion of Spring Mountain, Nevada," *Am. Jour. Sci.*, Vol. 17, 1929, pp. 461-72.

[47] Argand in *Eclogae geol. Helvet.*, 1916, p. 178 n. (quoted from Heim, *op. cit.*, p. 49).

area of this section, 100 square miles, will remain unchanged. If we compress the section to one-fourth its length at right angles to the strike, its height will increase four times. This means, that a shortening of only 7.5 miles will make the section 40 miles high. Since such a section could not stand up vertically, its recumbent front would advance more or less horizontally for a distance of 30 miles.

If we may think of the resulting structure as a huge fold, we may add that differential movements within the mass would produce innumerable subordinate folds. What we would actually see would certainly suggest a shortening by 100 miles rather than by 7.5 miles.

Salt domes. This exaggeration of the apparent shortening is best illustrated by the folds within the salt bodies of salt domes. Fig. 62

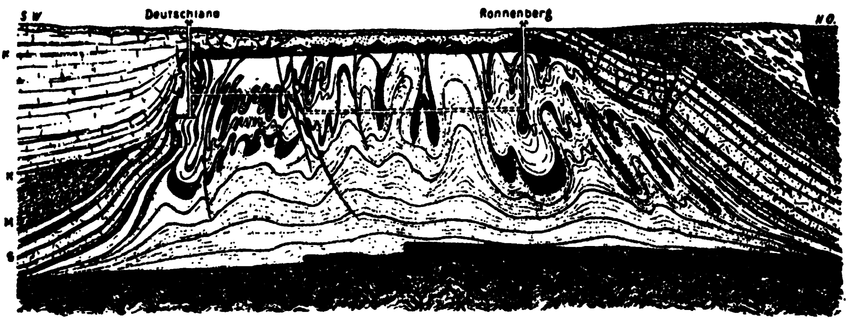


Fig. 62. Cross-section of the salt dome of Benthe-Ronnenberg near Hannover, north Germany, showing complicated folding of salt core. The conspicuous dark band separates the older salt body below from the younger salt above. The band itself represents three units: the older potash salts; the gray clay horizon; the "Hauptanhydrit." The younger potash salts are marked *Kj*.
(E. Seidl, 1927)

shows a section across the salt dome of Benthe-Ronnenberg, a few miles southwest of Hannover, in northern Germany.[48] The structure of the salt dome of Einigkeit, near Fallersleben, about twenty miles northeast of the city of Braunschweig, offers a picture that looks like a miniature reproduction of the *decken* of the Pennine Alps.

[48] Reproduced from Erich Seidl, "Die Salzstöcke des deutschen (germanischen) und des Alpen-Permsalz-Gebietes; ein allgemeinwissenschaftliches Problem," *Kali, Zeitschr. f. Gewinnung, Verarbeitung und Verwertung der Kalisalze,* Vol. 21, 1927, p. 25, Fig. 40.

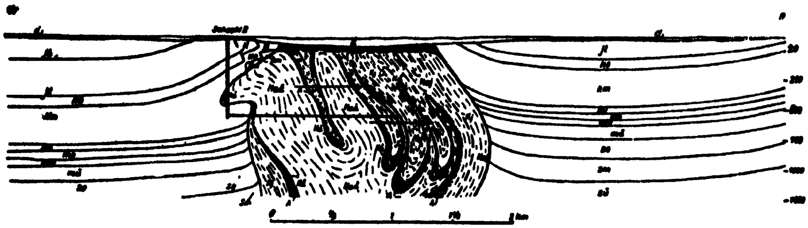


Fig. 63. Cross-section through the salt dome of Einigkeit near Fallersleben, north Germany, showing intense folding within the salt body. (*Naä* = older salt; *Kä* = older potash salt; *A* = anhydrite; *Naj* = younger salt; *Kj* = younger potash salt. *su, sm, so* = lower, middle, upper Buntsandstein (Lower Triassic); *mu, mm, mo* = lower, middle, upper Muschelkalk (Middle Triassic); *ku, km, ko* = lower, middle, upper Keuper (Upper Triassic); *jl* = Lias (Lower Jurassic); *jb* = "Brown Jura" (Middle Jurassic); *d* = Quaternary ("Diluvium"); *y* = cap rock.)
(P. Woldstedt, 1927)

(Fig. 63;[49] compare with Fig. 56, p. 195.) The similarity of the two structures extends also to the map picture. The reader should compare the interfingering of the older and younger salt masses in the map of the Benthe-Ronnenberg dome[50] with that of the Pennine *decken*, e.g., on Staub's map.[51] Note in both the contrast in the trend of the infolded *decken* in different parts of the area.

This comparison was made long ago by Stille and especially by Lachmann.[52] We are here concerned with the actual crustal shortening as against the deceptive appearance of enormous deformation. In the case of both sections reproduced above, the amount of horizontal shortening of the crust as a whole is at least very small, if not zero. The second one, according to Woldstedt, lies on a zone of tension fracturing. There is no sign of compressive movement in the attitude of the adjoining strata. Here the horizontal shortening certainly was practically zero. The vertical shortening of the adjoining stratigraphic column, due to the squeezing-out of the salt masses, may be measured in a few hundred meters. It is this shortening that really bears on our problem. The contrast between this small movement and the intricacy of the salt structure is impressive.

[49] Reproduced from P. Woldstedt, "Tangentiale Salzfaltung oder Vertikaler Salzauftrieb?" *N. Jahrb. f. Min.*, etc., Beilageband 58, abt. B., 1927, p. 595, Fig. 10.
[50] Erich Seidl, *op. cit.*, Fig. 33, p. 21.
[51] R. Staub, *Tektonische Karte der Alpen*, 1923.
[52] R. Lachmann, "Ueber den Bau Alpiner Gebirge," *Zeitschr. Deutsch. Geol. Ges., Monatsberichte*, Vol. 65, 1913, pp. 157-72, esp. Figs. 4 and 5, p. 165.

There is no means of connecting any such folded structure directly with the actual displacement involved in the direction of the major stress. Chamberlin's method of estimating crustal shortening of normal folded sediments, discussed earlier in these pages (p. 151), fails completely. It fails, because the structure has become discontinuous. The plastic core has broken across the mantling sediments. Such discontinuous structures produced by the differential advance of more plastic rock masses were called "plis diapirs" by Mrazec[53] ("Durchspiessungsfalten," "piercement" folds).[54] Stille uses the term "Injektivfaltung"[55] which he defines as "Faltung unter gesteigertem Vortriebe einzelner Faltenelemente." Where the injection is directed outward, toward the surface, he uses the term "ejektive Faltung." The term "injective folding" seems most suitable for use in the English language.

Injective folding produces stratigraphic offsets which suggest crustal displacements entirely out of proportion to what has actually taken place. This may be illustrated by a structure section across the Harli ridge near Vienenburg at the northern foot of the Harz Mountains (Fig. 64).[56]

On the south side, the Permian salt body has been thrown practically against the base of the Lower Cretaceous formations. Technically, the south side of the fault is the "downthrow" side. But the attitude of the rocks two miles on either side of the fault shows that displacement is not the result of a downward or upward movement of crustal blocks, but rather of a differential upward movement of the core of the anticline, in this case along one fracture plane. Now imagine the fault plane to be inclined 25° or 10° and apply the same reasoning. Then let us ask ourselves whether such differential move-

[53] L. Mrazec, *Les gisements de pétrole*, Bucharest, 1910.

[54] Mrazec has used this translation in a German review of one of his papers on local Roumanian geology in *Geol. Centralbl.*, Vol. 7, 1905-1906, p. 643, where the salt core is called "durchspiessend." K. Krejci has used the word "Durchspiessungsfalte" in his paper on "Der Bau der rumänischen Ölgebiete," *Geol. Rundschau*, Vol. 16, 1925, p. 12. This word D. C. Barton has rendered "piercement" folds in "American Salt-dome Problems," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 9, 1925, p. 1239.

[55] Hans Stille, "Injektivfaltung und damit zusammenhängende Erscheinungen," *Geol. Rundschau*, Vol. 8, 1917, pp. 90-142.

[56] Reproduced from P. Woldstedt, "Tangentiale Salzfaltung oder vertikaler Salzauftrieb?" *N. Jahrb. f. Min.*, etc., Beil. Band 58, 1927, p. 587, Fig. 4.

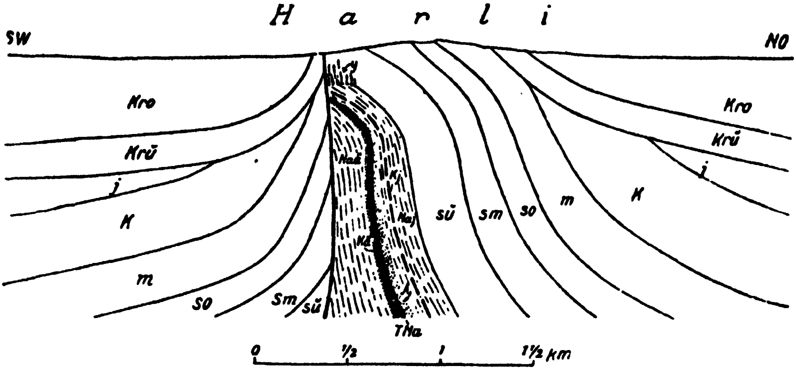


Fig. 64. Cross-section through the Harli ridge near Vienenburg, north Germany, showing a normal fault produced by the rise of the salt mass.

(*Naä* = older salt; *Kä* = older potash salts; *TNa* = gray salt clay; *A* = anhydrite; *Naj* = younger salt; *Kj* = younger potash salts; *y* = cap rock; *su, sm, so* = lower, middle, upper Buntsandstein (Lower Triassic); *m* = Muschelkalk (Middle Triassic); *k* = Keuper (Upper Triassic); *j* = Jurassic; *Kru* = Lower Cretaceous; *Kro* = Upper Cretaceous.)

(P. Woldstedt, 1927)

ments do not play a greater rôle on the larger scale of thrust faults of our welts than we are at present prepared to admit.

Cryptovolcanic structures. It would be wrong to think that such deceptive appearance of folding, far in excess of actual crustal shortening involved, is limited to structures produced in the specific presence of salt. In Fig. 65 is reproduced a section across the cryptovolcanic structure of Jeptha Knob, in Shelby County, Kentucky.[57] This is the smallest of three circular areas of disturbance found within the essentially undisturbed plateaus of Ohio, Kentucky, and Tennessee. All three were mapped by the writer. In all the center has been pushed up several hundred feet while a marginal zone has been depressed. Normal faults play more or less a rôle in all three structures. In detail the character of every cross-section is different from all the others.

If the section here reproduced were part of a linear structure, it would be taken for granted that the folding indicated an actual shortening of the surface. Here, however, the section is representative

[57] Reproduced from Fig. 6 (Section AB), opp. p. 214, of Walter H. Bucher, "Geology of Jeptha Knob," *Kentucky Geol. Survey*, Series VI, Vol. 21, 1925.

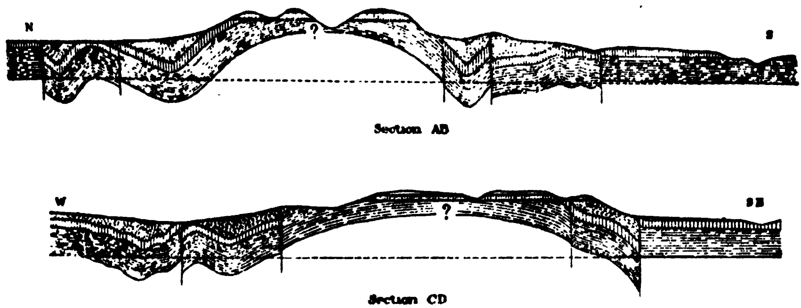


Fig. 65. Structure-section across the crypto-volcanic disturbance of Jeptha Knob, Ky.
Length of the section: about four miles.
The disturbed formations comprise Upper Orodovician formations of the Eden, Maysville, Richmond groups up to and including the Liberty formation, the latter in the centers of the synclines.
The overlying undisturbed rocks comprise Lower and Middle Silurian formations.
In the central portion, the structure of the disturbed rocks is simplified. It is quite confused with variable and steep dips.
The structure is circular in ground plan and is surrounded by undisturbed rocks on all sides. The faults are purely local.
(W. H. Bucher, 1925)

of what would be seen along any radial section through a circular structure.

Fig. 66[58] shows structure contours drawn on top of the Lower Silurian Brassfield formation in the Serpent Mound Structure, Adams County, Ohio. The lowest contours occupy the centers of the large oval troughs lined up along the margin. The highest surround the irregular blank area in the center. This central area is left blank because the Brassfield has been removed from it by erosion. The underlying Upper Ordovician layers of alternating thin shale and limestone which outcrop in the central area are thrown into minute crumplings which cannot be represented by contour lines.

Neither in this nor in any of the other cryptovolcanic regions is there a trace of volcanic materials or of hydrothermal action. Nor is there any salt known or to be expected in the underlying rock series. Obviously, the folding shown in this, as in the other cryptovolcanic

[58] The original was used in the writer's presentation of the Serpent Mound Structure before the Geological Society of America, in 1920. (See *Bull. Geol. Soc. America*, Vol. 32, 1921, pp. 74-5.) A detailed report on the structure will be published by the Ohio Geological Survey.

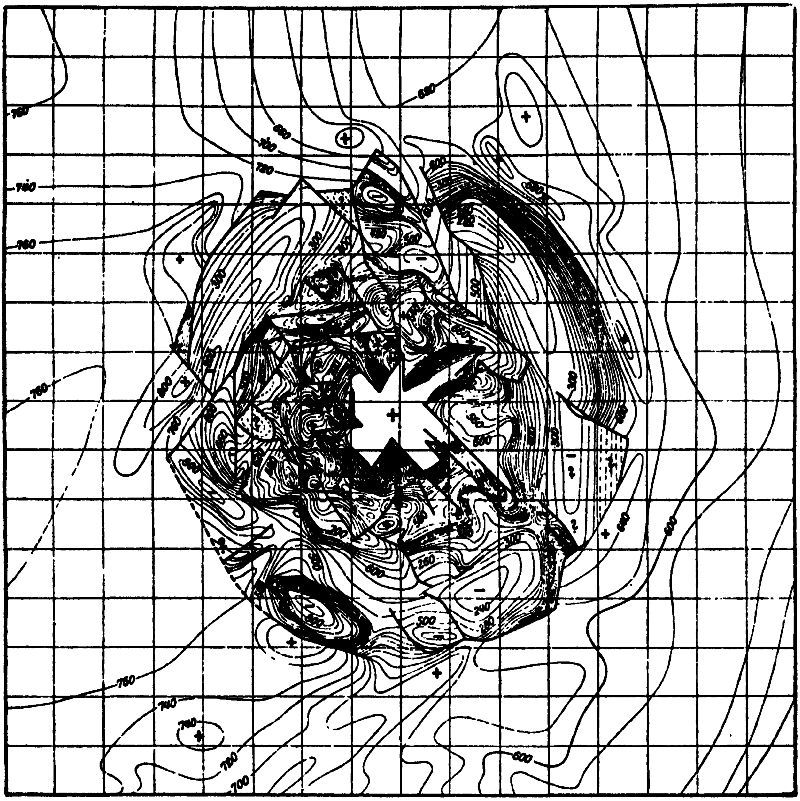


Fig. 66. Tectonic map of the crypto-volcanic disturbance in Adams County, Ohio. The structure is represented by contours drawn on top of the Brassfield (Lower Silurian) formation. Contour interval: 20 feet. Note the deep oval basins along the outside of the structure reaching to or below 200 feet above sea level. In the irregular cross-shaped central area the highest contour shown is 1,000 feet above sea level. Within this area the structure is greatly confused, with strike and steep dips varying from point to point. Here locally all formations of the underlying Cincinnatian (Upper Ordovician) series come to the surface down to the Middle Eden formation under conditions which point definitely to explosive action.

(W. H. Bucher, 1920)

regions, was not produced by direct lateral pressure, which in this case would have had to be directed from the center outward. The writer thinks that it came about when the central plug was forced upwards. The overlying inert few thousand feet of chiefly sedimen-

tary rocks were broken and lifted irregularly and adjusted themselves "plastically" to the spaces that would otherwise have been left as voids in the structure. It may be that in the American cryptovolcanic structures the uplift was a rather sudden event, perhaps even explosive.[59] But this question does not concern us here. This interpretation is adduced here merely to show another type of deformation which may result in complicated folds which are not the result of tangential shortening of the crust. It seems probable that in zones of orogenic folding similar adjustments play an important rôle.

Salt structures of southwestern Persia. The most striking cases of plastic thrust sheets on a relatively small scale have been described by Busk from southwestern Persia.[60] The region from which his illustrations are taken, lies about in the latitude of ancient Babylon in the extraordinarily rugged country along the southwestern foot of the high folded ranges which border the Mesopotamian plains on the northeast. Fig. 67 shows a section through the Masjid-i-Sulaiman oil field.[61] From it the essential elements of structural history may be

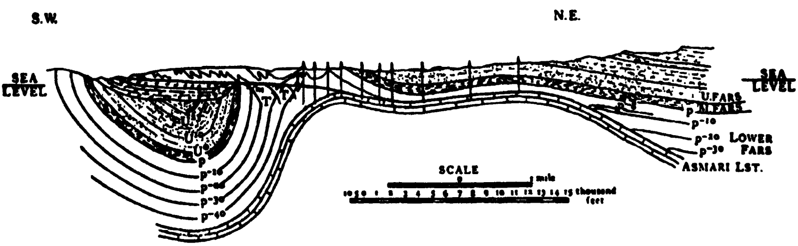


Fig. 67. Structure-section across the Masjid-i-Sulaiman oil field, southwestern Persia.

A thrust sheet of the plastic lower Fars series (largely gypsum and clays) emerging from an anticline and overriding the adjoining syncline to a distance of two miles. Note the thinning of the lower Fars series on the nearly horizontal gentler limb of the anticline between the stronger beds above and below.

(H. G. Busk, 1929)

[59] For a discussion of the mechanism of the American cryptovolcanic structures, see Walter H. Bucher, "Cryptovolcanic Regions," *Jour. Washington Acad. Sci.*, Vol. 18, 1928, pp. 521-4.

[60] H. G. Busk, *Earth Flexures*, Cambridge Geological Series, Cambridge, 1929, pp. 77-95.

[61] Reproduced from Fig. 75, p. 87, of Busk's paper.

read. Only the top of a thick series of Cretaceous, Eocene, and Lower Miocene marine formations is shown in the section, namely, the top of the Lower Miocene Asmari limestone. Above it are five thousand feet of the lower Fars series, largely gypsum and clays. These are followed by the brackish water sandstones and clays of the middle and upper Fars series. Unconformably across these rest the fluviatile clastics of the Pliocene Bakhtiari series which are in part coarse and massive conglomerates in the higher levels of the series. These clastics were laid down contemporaneously with the folding of the Miocene and older beds. In the synclines they reach thicknesses up to fifteen thousand feet, and spread originally, of course, across the whole region.

Wherever this thick and massive cover of conglomerates was eroded away from the crests of anticlines down to the lower Fars series, the plastic gypsum-clay mass began to move outward, perhaps solely under the static weight of the synclinal loads. It crept forward bodily over the eroded edges of the steep limb of the adjoining syncline. "In the process the gypsum itself became highly folded; at the front of each advancing sheet it often became rolled and inverted again and again, while further behind it took up the form of highly compacted isoclinal folds with nearly vertical axes."[62] The texture of the thrust mass is described by Busk as "gypsum quasi-schist." "This rock consists in the main of gypsum with inclusions of unaltered clay shale and limestone locally derived. The gypsum appears to have flowed around the inclusions. The rock is more than a fault breccia, as it may occur many hundreds of feet thick, and the whole of a thrust sheet may in fact be composed of it."[63] As in the case of schists, it is sometimes impossible to tell whether the partings are bedding planes or planes of flow.

The gypsum *decken* may show imbricated structure such as is pictured in Fig. 68.[64] Busk introduces three graphic terms. Where thrusting has taken place in one direction, as (essentially) in the case of the major thrust of Fig. 68, he applies the term "gamma

[62] *op. cit.*, p. 85.
[63] *op. cit.*, pp. 87-8.
[64] Reproduced from Fig. 78, p. 89, of Busk's paper.

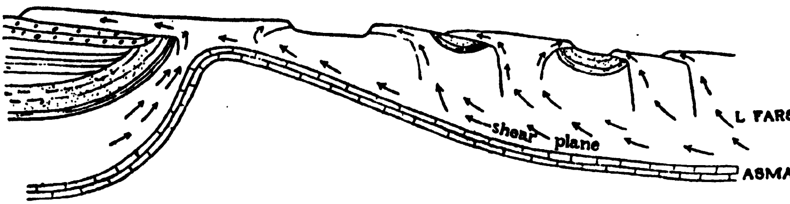


Fig. 68. Structure-section of an anticline in the plastic lower Fars series (largely gypsum and clays) of the Bakhtiari country in southwest Persia.

Note the major overthrust on the steeper limb and minor imbrications on the gentler limb ("gamma" and "omega" structures). Note also that the dominant overthrusting is directed toward the steeper side even far down on the gentler limb.

(H. G. Busk, 1929)

(Figs. 67 and 68 reproduced from *Earth Flexures*, by permission of the Cambridge University Press)

structure," in allusion to the Greek letter Γ. Where a thrust mass is bounded by thrusts in opposite directions, as above the word "shear" in Fig. 68, he speaks of an "omega" structure (Ω).[65] For the case of a fault block that rose without overthrusting on either side, he uses "iota structure," with reference to the capital letter I.

"There is ample evidence to show that these thrust movements have continued down to the present day, and are still continuing. The front of each advancing gypsum sheet rises abruptly as an escarpment, cut into facets by consequent streams which plunge from the surface as hanging valleys."[66] Busk describes and figures in detail cases in which the advancing thrust sheets have obstructed the existing drainage. His diagrams also show that the tops of the thrust sheets are surprisingly flat. Physiographers who are quick to recognize peneplains should study the factors of erosion in detail in the field. They might perhaps benefit from this small-scale model as well as the structural geologists.[67]

We are here concerned with but one aspect of these remarkable structures. Busk's assumption that the flowage which led to the formation of the gypsum *decken* was the result of static stresses alone, may perhaps be open to doubt. But there can be no possible doubt that the amount of thrusting now seen in the region of the Masjid-i-Sulaiman oil field is far in excess of whatever actual crustal

[65] *op. cit.*, p. 88.
[66] *op. cit.*, p. 90.
[67] See Figs. 80 to 83 of Busk's book.

shortening may have been responsible for it, that possibly the latter was even zero. Now it is instructive to compare Fig. 68 with the diagrams in which Argand has represented his concept of the nature of crustal deformation (Figs. 69).[68] Argand's diagrams refer to what he calls "plis de fond," a term which is wider than our "welts." For our purposes, we may interpret the sections as illustrating "welts." The lined portions of the sections represent metamorphic

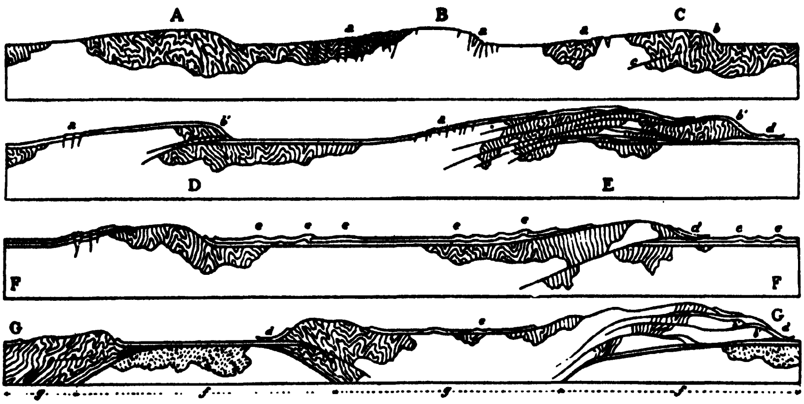


Fig. 69. Diagrammatic structure-sections illustrating the nature of deformation of the outer crust as interpreted by Argand.
A = crustal fold ("anticlinal de fond").
B = crustal fold with longitudinal fractures (*a*).
C, D, E = different stages of the development of thrust sheets from a crustal fold.
FF = crustal folds and marginal folds (*e*) in the mantling sediments.
GG = inactive old crystalline masses (*f*) overriden by the actively deforming crystalline rocks of the crustal folds (*g*). Portions of the sedimentary cover carried along by the advancing thrust sheets (*d*).
(E. Argand, 1922)

rocks. Old granitic intrusives are left blank. The sedimentary mantle is obvious and indicates the scale of the sections. Each section is intended to represent several hundred miles. Busk's diagram (Fig. 68) covers but several miles. Yet the two structures bear many resemblances. Is it not reasonable to say that if isoclinal folds and thrust faults can arise on the small scale of the Persian folds with very little if any horizontal crustal movements, the amount of crustal shortening

[68] Reproduced from E. Argand, "La tectonique de l'Asie," *Congr. géol. internat., XIII, 1922, Compt. Rend.*, 1er fasc., p. 335, Fig. 5.

implied in the structure of Alpine mountains may have been greatly overestimated in the past?

Critical comments on the interpretation of Alpine structure. In the case of the Alps, the largest source of error in estimating the amount of crustal shortening lies in the theoretical basis of the *decken* theory. The structure of the Alps is not so clearly exposed as to leave no room for divergent interpretations. In Fig. 70[69] the accessible part of the

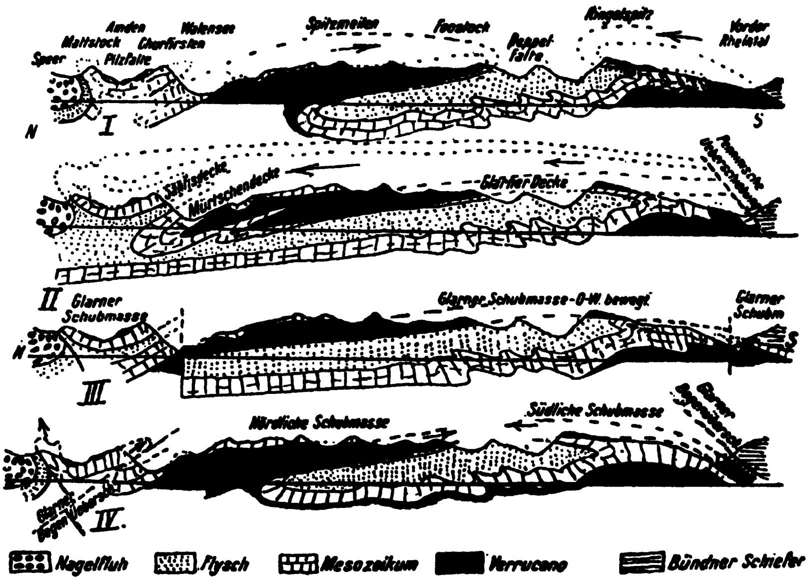


Fig. 70. Four structural interpretations of one and the same cross-section, drawn in a north-south direction across the Alps in Canton Glarus, Switzerland.

I—Two recumbent folds moved from opposite directions ("Doppelfalte"). (Heim, older interpretation.)

II—A single, long drawn-out recumbent fold ("Falten-Decke"). (Heim and most Swiss geologists, current interpretation.)

III—A thrust sheet, thrust from east to west (at right angles to the paper) in the central portion, bounded by normal faults. (Rothpletz.)

IV—Local thrust sheets moved along shearing planes inclined in opposite directions. (Mylius.)

Nagelfluh = Miocene; Flysch = Eocene; Verrucano = Permian; Bündner Schiefer = schists largely of Mesozoic age.

(S. von Bubnoff, 1921; reproduced from *Die Grundlagen der Deckentheorie in den Alpen*, by permission of E. Schweizerbart'sche Verlagsbuchhandlung [Erwin Nägele])

[69] Reproduced from S. von Bubnoff, *Die Grundlagen der Deckentheorie in den Alpen*, Stuttgart, 1921, p. 68, Fig. 34.

structure is the same in all four sections. It represents a distance of some 28 miles in the Alps of the Canton Glarus in Switzerland. The first section illustrates the structural interpretation which prevailed before the rise of the *decken* theory shown in the second section. The last two sections represent the views of the two best known opponents of the orthodox *decken* theory.[70] Note especially that in the third section the central portion is assumed to have been moved in an east-west direction, that is, at right angles to the plane of the section. The last section is almost a return to the first, but replaces folding in part by thrusting.

Of the four interpretations, that in terms of *decken* involves by far the greatest mechanical difficulties. Yet it has won out with every one of the men who have spent sufficient time in detailed field study. It has gained acceptance because it alone ties together all observations in their three-dimensional relations into a consistent logical picture. The observations include the sedimentary facies as well as the structure. The more both become known in detail, the more they fit into the *decken* scheme. This seems sufficient evidence that, for units such as shown in the diagrams, the *decken* interpretation is essentially correct.

But this does not mean necessarily that the principles developed in the *decken* interpretation are equally valid when applied to the largest structural units of the Alps. Two principles in particular which underlie the extreme interpretations of Alpine structure in terms of *decken* constitute an extrapolation beyond the limits of actual observation: (1) The major *decken* formed uniformly along the whole length of the Alps. (2) Throughout the Alps, all thrust masses have been overthrust northward, or at least from the inner toward the outer border. There has been no thrusting in the opposite direction.

The first of these principles is quite at variance with our law 7. The least deformed of the Alpine welts, the "autochthonous massifs," certainly did not form as a uniform chain along the whole length of the Alpine front. Their arrangement is quite in harmony with law 7. Is it not more probable that the inner-Alpine welts which became transformed into the great crystalline *decken*, also arose in the form

[70] A. Rothpletz, *Das geotektonische Problem der Glarner Alpen*, Jena, 1899; Hugo Mylius, *Geologische Forschungen an der Grenze zwischen Ost- und Westalpen, München*, 1912-13, esp. Part II, 1913.

of localized masses rather than as uniform crustal folds? Argand's and Staub's great sections across the Western Alps look so formidable, because every *decke* which is overlapped by another one, is assumed to continue quite unchanged underneath the other one and should be found emerging again several hundred miles away along the strike. The slates on my roof overlap one another. Yet I do not assume that beneath the highest one there lies a thickness of slate comparable to that of all other slates that lie at right angles to the strike.

The writer knew that when he compared the southern Rocky Mountains with the Alps, he placed side by side two regions which traditional European doctrine considers opposite poles of structure. Even American geologists have to get accustomed to the idea of large thrust faults in the Colorado Rockies. The long narrow welts of the southern Rockies are readily represented by long continuous lines marking the axes of uplift. Yet the geological map shows a significant *en échelon* pattern of individual welts with oblique as well as longitudinal depressions. The synclinal axis, with its younger sediments, on the east side of the Ute Pass fault, is a good example. The larger problems of the Central Alps may perhaps be solved when a more complex pattern of embryonic welts is assumed[71] than that offered as first approximation by Argand.

As soon as the problem of inner-Alpine structure is viewed in this light, doubt is cast on the second principle. For in the primitive welts of the southern Rockies we have overthrusts in opposite directions on opposite sides of one welt. Because on the smaller scale of single *decken* the assumption of thrust in opposite directions has been found inapplicable, it has become taboo throughout Alpine structural interpretation. Yet some of the "*fenster*" of the inner-Alpine *decken* may be oblique synclinal zones overwhelmed laterally from opposite sides by the edges of rising *en échelon* welts. To the outsider, at least, it seems as if this possibility had not been considered adequately. If, for instance, much more of the imposing "St. Bernard Decke" of the Swiss and French Alps were autochthonous than is now assumed, the estimate for crustal shortening in the Alps would be greatly reduced.

[71] For the contrast between the Western and Eastern Alps, this has been advocated recently by B. Lindemann in *Kettengebirge*, Jena, 1927.

Résumé. The outcome of this discussion of Alpine deformation may be generalized and formulated as follows:

Opinion 23. The actual amount of crustal shortening involved in orogenic folding is much smaller than the resulting structures lead one to expect.

6. The Plunger Effect of Overthrust Masses

Buttresses and marginal folds. With the perspective gained in the three preceding chapters, we return once more to the broader relations that exist between welts and their forelands.

First of all, we now understand why experiments made with the traditional compression box have been so successful in reproducing the structure of folds. Two essential elements of such experiments do not, at first sight, seem to have counterparts in nature: the plunger, and the bottom of the compression box, which allows the strata to be sheared off. These same elements are present in the instructive device suggested by Tokuda.[72] He lays a moistened piece of soft paper (tissue paper) on a glass plate and produces slight horizontal displacements by pushing the paper here and there with a finger. This simple device is instructive in two ways. (1) It shows that slight horizontal movement may produce astonishingly large wrinkles; (2) that the pattern of these wrinkles may be made to simulate any one of those characteristic of welts. The difficulty here as in the pressure-box experiments is to find the equivalent for the plunger (or the finger which takes its place in Tokuda's device).

The view of welt formation suggested in these pages (opinions 17 to 19) implies a real plunger mechanism for all marginal folding. As the crust is shortened by downward expulsion of crustal matter along a mobile belt, the less yielding rock materials of the uppermost few miles of the crust are piled up into smaller space. At first they are thrown into folds with large radii of curvature, true crustal folds, the primary welts. With further compression, these may fracture and encroach on the foreland in the form of thrust sheets; or they may yield in more "plastic" fashion and be forced onto the foreland as *decken.*

[72] Sadakazu Tokuda, "On the Échelon Structure of the Japanese Archipelagoes," *Japanese Jour. Geol. Geogr.*, Vol. 5, 1926-1927, pp. 41-76.

There the advancing thrust sheets and *decken* assume the function of a plunger which shears off the mantle of sediments or slices off a shell involving even the crystalline substructure. This marginal deformation we have called "passive" to contrast it with the plunger action of the outward advancing folds and thrust sheets of the "active" belt.

With this picture in mind, we may view a few additional details of the structures produced in the course of the marginal deformation produced by the plunger action of active welts.

First there are the complications which arise through differences in the strength of the rock materials in the outermost few miles of the crust. Earlier in this book we came to the conclusion that the localization of the first furrows and with them of the mobile belts as such, which involves the crust as a whole, takes place without regard to variations in the strength of rocks near the surface (p. 202). In the course of the superficial marginal deformation, on the other hand, differences in the strength of rock materials in the outermost part of the crust play an important rôle.

Between the Adirondacks and the Green Mountain welt, for instance, the rocks of the Appalachian Valley are crowded in remarkable fashion. Here, in a belt three to ten miles wide, from three to seven thrust faults[73] pile up the sediments in front of the rigid swell of the Adirondacks which clearly acted as a buttress.

An excellent illustration of this crowding of marginal folds against an obstacle is shown in Fig. 71.[74] This is part of the "Tektonische Übersichtskarte des Jura-Gebirges" drawn by Heim in 1914 and published in Vol. I of his *Geologie der Schweiz*. It shows the northern portion of the Jura folds. The width of the black lines which mark the axes of the anticlines is proportionate to the height of the folds. Short dashed lines closely crowded parallel to the axial lines of folds indicate areas covered by thrust masses. Longer dashed lines indicate faults. A line of dashes with cross-bars marks the borders of the Rhine Valley graben. To the east of the graben lies the crystalline mass of the Black Forest swell ("Schwarzwald"). On its south foot it is overlain by plates of Mesozoic formations broken by numerous

[73] A. Keith, "Cambrian Succession of Northwestern Vermont," *Am. Jour. Sci.*, 5th ser., Vol. 5, 1923, p. 104.

[74] Reproducing a part of Pl. xx, opp. p. 548, of Alb. Heim, *Geologie der Schweiz*, Vol. I.

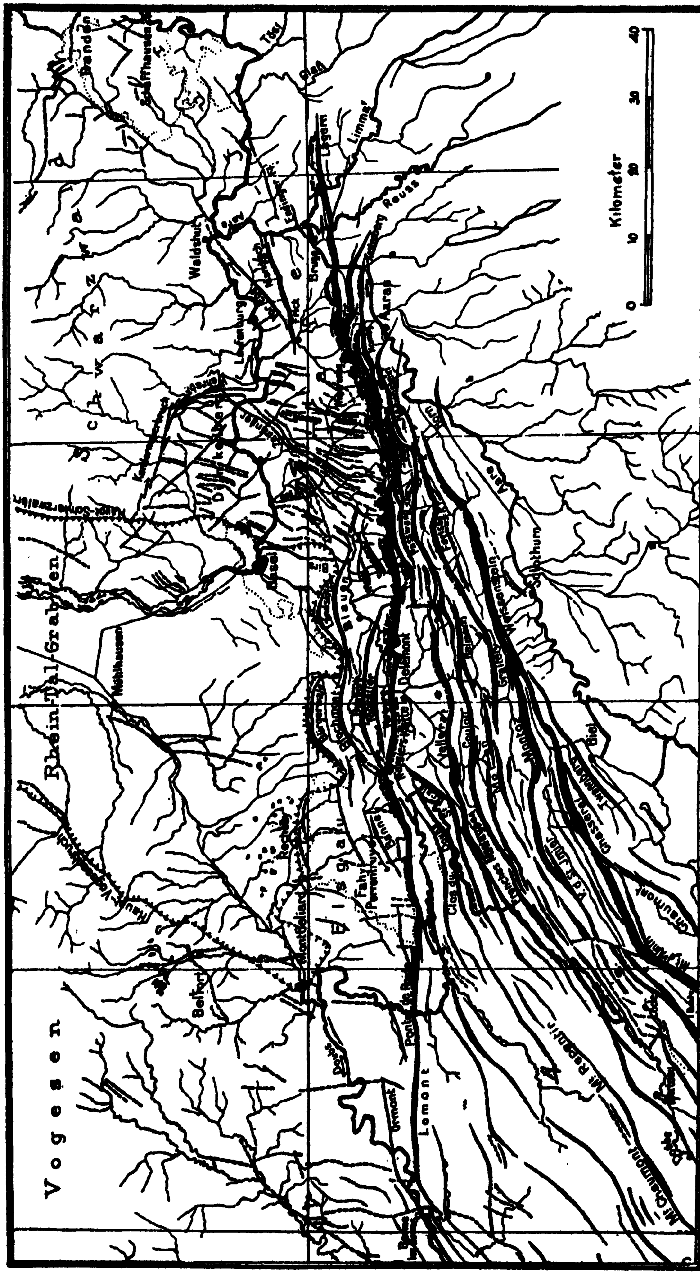


Fig. 71. Tectonic map of the northeastern part of the Jura Mountains, in Switzerland. (Compare with Fig. 72.)
Heavy black lines = axes of anticlines, width of line proportional to height, i.e. to the intensity of folding.
Dashed lines, one or several in front of and parallel with anticlinal axes = overthrust portions of anticlines.
Dashed lines more or less at right angles to axes of folds = normal faults.
Lines formed by patterns resembling dip and strike symbols placed end to end = outline of Rhine Valley graben.
(Alb. Heim, 1919; reproduced from *Geologie der Schweiz*, by permission of Bernhard Tauchnitz A. G.)

north-south trending faults east of Basel. West of the graben lies the swell of the Vosges Mountains ("Vogesen").

Now note how the fan of folds converges from the west toward the east. The arrangement is part of the semicircular pattern produced in the mantle of sediments by the pressure of the thrust masses of the Préalpes, which probably played the part of a "plunger" in this case (p. 192). Yet the way the folds pile up against the south foot of the Black Forest swell shows dramatically in the abrupt narrowing of the folded belt and the piling up of thrust masses.

This illustration is particularly useful because it shows at the same time the opposite effect. Where the Rhine Valley graben separates the crystalline masses of the Vosges Mountains and the Black Forest, the folds lurch forward into the gap. To see this clearly, note on the map (Fig. 71) the normal almost straight outer edge of the Jura folds. It runs from Lomont Mountain in the west to the Lägern ridge in the east. It is the line prescribed by the south foot of the common front of the Vosges and the Black Forest. Note that additional folds lie north of the main outer fold of the Jura only along the southern end of the Rhine graben. Here the more rigid basement of the crystallines lies probably over one and one-half miles lower than in the adjoining swells. This caused the surficial folds to surge forward into the gap.

This map leaves no room for doubt that here the differences in the strength of rocks near the surface have influenced the trend of deformation. Illustrations could easily be multiplied from all regions of intense superficial folding.

Even on a larger scale, the distribution of swells and basins in front of a line of welts may be expected to influence the grouping of the superficial "marginal" folds. In the case of the Alps, the development of "marginal" folds in the Jura and the sub-Alpine chains of France is clearly influenced by the depressions that separate the swells of the Vosges, the Central Plateau, and the crystalline massif between Toulon and Cannes on the Mediterranean coast (Monts des Maures).

In the southern half of the Appalachians, for example, the modifying influence of swells in the foreland may be recognized in a similar way. Here huge overthrusts mark the western border of the Blue Ridge welt, from southern Virginia into northern Georgia. Their presence accounts for the vast arc of marginal folds that extends from

Rome, Ga., to Roanoke, Va. The curvature of this arc of marginal folds does not correspond to the strike of the inner structure of the crystalline welts.[75] It is clearly a surficial phenomenon connected with the excessive local outward thrusts. The center of this arc lies opposite the depression that separates the Nashville swell from the Jessamine ("Cincinnati") swell. The outer edge of the arc shows definitely the influence of the presence of the crystalline rock nearer the surface in the swells. Where the western flank of the arc meets the relatively rapidly rising crystalline core of the Nashville dome, the outlying Sequatchie anticline rises. Correspondingly, on the northern flank which presses against the foot of the Jessamine dome, the Pine Mountain fault block[76] is located. Between the two there is a space of fifty miles or more in which there was no such outlying horizontal shearing and faulting. This space corresponds in position to the depression between the two welts where the crystalline basement lay too low to have a similar buttressing effect.[77]

We may formulate the outcome of this discussion as follows:

Opinion 24a. Bodies of crystalline rock materials near the earth's surface act as "rigid bodies" in the course of the superficial (marginal) folding of the weaker sediments.

While the difference between the stronger crystalline and the weaker sedimentary rocks is thus an important factor in the superficial marginal folding, giving rise to "buttresses" and "obstacles," it seems to play little or no part in localizing mobile belts and controlling their trend. This appears to follow from the autonomous fashion in which later geosynclines often cut across older folds and across preexisting swells and basins. (See Chapter XI.) This behavior agrees with observations made by the writer in his experiments with hollow spheres (pp. 119-23). The inner surfaces of the paraffin

[75] This is in contrast to the arcuate shape of the outcrops in Pennsylvania and New York, where the curve of the sedimentary folds runs parallel to the swerving of the crystalline axis itself. If the writer is correct in this interpretation, the southern salient of the Appalachian belt differs fundamentally in character from that of Pennsylvania and New York.

[76] Wentworth has called this the "Cumberland Block" in a valuable paper: Chester K. Wentworth, "Russell Fork Fault of Southeast Virginia," *Jour. Geol.*, Vol. 29, 1921, pp. 354-69.

[77] Compare Bailey Willis' *Geologic Map of North America*, 1:5,000,000, after completing the structure of "Pine Mountain block" from the sketch in Wentworth's paper quoted above.

spheres he used were quite uneven, causing the thickness to vary considerably from point to point, in contrast to the glass spheres which had smooth inner and outer surfaces and nearly constant thickness. The patterns of the tensional fracture lines produced by water freezing in the spheres were correspondingly much more irregular in the paraffin spheres. Yet, individual fractures cut across thick and thin portions with little regard to the distribution of the irregularities, quite like furrows on the earth's surface.

The reason for this behavior seems to be that under tension the position and form of any line of yielding is determined by the algebraic sum of the influences of all inhomogeneities throughout the whole thickness of the crust of which those in the outermost few miles constitute only a relatively insignificant part.

Opinion 24b. The distribution of crystalline and sedimentary rocks at and near the earth's surface does not have much influence on the location of a new mobile belt, since the combined effects of all inhomogeneities throughout the whole thickness of the crust determine the location and trend of any new line of yielding.

Flaws in marginal folds. When a relatively thin superficial layer of the crust is sheared off from its base by the localized "plunger" action of a larger thrust mass, differential horizontal movement along essentially normal fracture planes is apt to take place. In the first volume of his *The Face of the Earth,* in 1885, Suess pointed out the significance of such fracture planes along which movement was essentially horizontal. He applied to them the term "Blatt" (plural: "Blätter"). This term has long been generally adopted by German-speaking geologists. Sollas, in the English translation (1904), coined the word "flaw," "a word which, like the feature itself, has some fellowship with 'fault.' "[78] Two examples of such flaws will be quoted here from Heim's *Geologie der Schweiz,* because they have been studied in unusual detail.

One is that of the flaws in the folds of the Jura Mountains, shown on Heim's tectonic sketch map (Fig. 72).[79] In his elaborate discussion, Heim calls attention to the symmetrical arrangement of the ten major flaws. They are absent on the extreme ends. The fracture

[78] Hertha B. C. Sollas and W. J. Sollas, *The Face of the Earth,* Vol. I, Oxford, 1904, p. 120. The French translation uses the word "décrochements."

[79] Reproduced from Alb. Heim, *Geologie der Schweiz,* Vol. I, 1919, p. 615, Fig. 103.

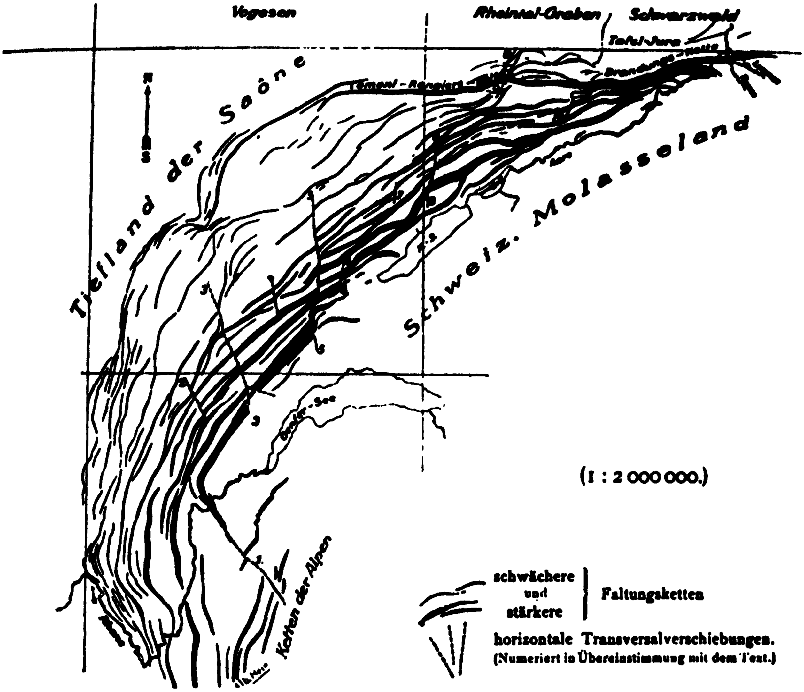


Fig. 72. Tectonic sketch map of the Jura Mountains, Switzerland, showing the axes of the anticlines offset by flaws.

The width of the solid lines indicates the relative height and intensity of folding of the anticlines.

(Alb. Heim, 1919)

which involves the greatest amount of displacement, occupies the exact center of the arc (No. 5 on the sketch). The two next in importance lie similarly spaced with reference to it, about thirty-five kilometers southwest and northeast of it. The smaller ones again lie fairly evenly spaced between the others. This symmetrical arrangement must be due to stresses that affected the plate of sedimentary rocks as a whole as it underwent folding. The flaws clearly are shearing fractures due to the stretching along the arc such as is inevitable under surficial plunger action.

In standard laboratory experience, shearing stresses appear in two systems intersecting in such a way (in rock materials near the

earth's surface) as to face the obtuse angle in the direction of the maximum tensional stress. Here in the Jura folds, one system predominates greatly. The other is not entirely absent. The only larger one of the complementary system represented on Fig. 72 is seen at the southeastern end of fracture No. 3. The suppression of one of the two conjugate shearing planes is the rule wherever forward movement is favored on one of the two sides of the shearing planes. Here, in the Jura folds, in every case the folds on the northeastern or eastern side of the flaws have advanced northward with reference to the southwest side.[80]

The relation of the flaws to the anticlines shows that they came into existence in the course of folding, after the main lines of folding had been established, but before they were completed. Note, on Fig. 72, how the major axes of folding can be recognized on both sides of the flaws. Yet the final pattern of the folds shows a good deal of independent movement on opposite sides of each fracture. These last movements in the Jura Mountains have taken place in early Pliocene (post-Sarmatian) time.

A comparable system of fractures is found in the Säntis Mountains,[81] south of the Lake of Constance and west of the Rhine valley. Their marvellously exposed folds show compression of a thin series of sediments (less than a mile thick) carried one step farther than in the Jura Mountains. Heim called them "ein temperamentvoller Jura." This system of folds comprises Cretaceous formations only which rest as *decke* on the Tertiary Flysch along the outer border of the Swiss high Calcareous Alps.

In the northeastern half of the mountain system fractures cut obliquely across the folds.[82] The fracture planes are practically vertical. Movement along them has taken place chiefly in a horizontal direction. This is proven by the relative position of the folds on

[80] For a general discussion of the arrangement of shearing planes corresponding to different attitudes of the principal stresses, the reader is referred to the writer's paper on "The Mechanical Interpretation of Joints," *Jour. Geol.*, Vol. 28, 1920, pp. 707-30; Vol. 29, 1921, pp. 1-28.

[81] The monograph on this region and the maps and sketches accompanying it constitute a veritable classic which deserves being studied by every student of structural geology. Alb. Heim, Marie Jerosch, Arn. Heim, und E. Blumer, "Das Säntisgebirge," *Beitr. z. Geol. d. Schweiz*, N. F., Lief. 16, 1905 (with atlas and maps 1:25,000).

[82] See Pl. XVII, opp. p. 360, in Alb. Heim, *Geologie der Schweiz*, Vol. II, 1921.

opposite sides of a fracture and by the attitude of abundant grooves on the slickensided fault planes.[83]

The horizontal displacement along these fractures varies from point to point, reaching a maximum of 800 meters (2,600 feet).

All these fractures die out in the underlying Eocene Flysch. They are strictly confined to the folded Cretaceous thrust mass (*decke*). Here, as in the corresponding flaws of the Jura Mountains, the pattern of the fractures is that which must arise (near the earth's surface) from the action of stresses directed in such a way that the maximum principal compressive stress lies at right angles to the axes of the folds, while the minimum principal stress (representing virtual or actual tension) lies parallel to them.

Here, as on the Jura folds, the oblique fractures were formed in the last phase of folding. In the Säntis Mountains, this occurred very recently, probably in Middle Pleistocene time. The lines of dislocation cut across the established topography.[84] In two places at least, where a fracture cuts across a ridge, the ridge on one side of the fracture was pushed forward across the valley in front of its continuation on the other side of the fracture, blocking the stream and transforming it into a lake. The very fact that these lakes still exist (Fählensee, Seealpsee) shows how extraordinarily recent these last horizontal movements have been.

The significant fact in these and similar cases of flaws is that their very existence implies that the mass undergoing deformation found it as easy or easier to spread laterally than to rise vertically. This is possible only at the surface of the earth and not at any depth. The presence of such fan-shaped groups of flaws,[85] then, offers an independent evidence of the extreme shallowness of deformation, such as characterizes the "plunger" action of the overriding fronts of rising welts.

Alternative interpretations. The plunger action of thrust masses, as described in the preceding pages, is by no means generally recognized. We will do well to view it once more, this time more directly in its mechanical aspects. In the best known example, that of the Jura

[83] These striations dip on the average 12° northward.

[84] Alb. Heim, *Geologie der Schweiz*, Vol. II, p. 369.

[85] See also the experiments by T. A. Link described in "En Échelon Folds and Arcuate Mountains," *Jour. Geol.*, Vol. 36, 1928, pp. 526-38, especially experiment No. 50, Fig. 4, p. 531.

folds, the distance from the outer edge of the outermost thrust masses of the Alps responsible for the folding, to the outer edge of the sheared-off plate, measures about fifty miles. To it should be added between five and ten miles by which the plate was shortened through folding. Over this distance a sheet of sediments at best not much over one mile thick, was sheared off its base and thrown into complex wrinkles by thrust masses which acted on it after the fashion of our fingers when we produce wrinkles on moist tissue paper laid on a glass plate.

The mechanics of such a process are very different from those which figure in traditional geological discussions. We are apt to look at the engineer's figures for the crushing strength of rocks and then look at the strata exposed in the folds and say, "such sediments are not competent to transmit stresses over long distances." Yet they could hardly be less competent to "transmit stresses" than moist tissue paper. The important point we must recognize is that it is not the absolute value of any coefficient of strength which determines the behavior of rocks under stress, but its relative value in comparison with all others involved. The deciding factors in the folding which results from plunger action are the frictional resistance along contacts of different levels and the shearing strength of the sediments.

Geologists have long been impressed with the difficulty of harmonizing the seemingly low crushing strength of sediments (at little depth) with the need of transmitting stresses over the great distances over which folding has taken place. Consequently, they have sought to account for the folding by conditions which are compatible with the low crushing strengths of sediments. Three possibilities have suggested themselves:

(a) The tangential force may be applied at least in part, from above so that it leads to a shearing off, provided the shearing strength and the frictional resistance of the materials in some "lubricating" layer are smaller than the average crushing strength of the rocks involved. The "plunger" action we have assumed here is one such case. In the Jura Mountains, the formation which acted as a "lubricant" consisted of salt-bearing clays and shales, the so-called "Anhydrit Gruppe" (middle Muschelkalk = middle Triassic).

(b) The force which leads to the folding may reside *within* the folded sedimentary series. This would be true if the folding were the

result of gravitative slumping. This view was developed by Reyer[86] and especially by Haarmann.[87] It is probable that a varying, perhaps rather large, part of marginal folding is due to gravitative settling in Haarmann's sense.

(c) The force which causes the folding may attack the sediments *from below* in the form of a deep-seated current which throws the surface into wrinkles just as in a sluggish stream the water flowing at depth wrinkles the scum on its surface. This simile has been taken directly from a recent book by Cloos.[88] In it Cloos has attempted to interpret the realities of the larger structural features of North America and north and central Europe in terms of the deep-seated movements of matter, currents which drag an inert and relatively more rigid crust with it, wrinkling it here, straining and cracking it there, and finally breaking it into pieces which, like cakes of ice in a river drift, pile one on top of the other in overthrust slices or shove one beneath the other in underthrusts. In this hypothesis we recognize "continental drift" in inverted form: the active drift has been turned passive. The relative movement is the same;[89] but very different physical causes must be sought if it is recognized as valid.

One cannot read Cloos' or Argand's analyses without being impressed with the advantage the hypothesis offers in correlating many of the large features of continents. Yet the capacity of a hypothesis to organize otherwise uncorrelated facts does not constitute in itself proof of its physical reality. In order to be acceptable, the hypothesis must prove to be consistent with the detailed facts and all the concepts derived from them.

The writer cannot accept the hypothesis of subcrustal flow because it is inconsistent with the concept of the crust derived in these pages

[86] See, e.g., E. Reyer, *Geologische Prinzipienfragen,* Leipzig, 1907, p. 148.

[87] E. Haarmann, "Die Oszillationstheorie," Stuttgart, 1930.

[88] Hans Cloos, "Bau und Bewegung der Gebirge," *Fortschritte der Geologie und Palaeontologie,* Band VII, Heft 21, Berlin 1928, p. 314.

[89] Hans Cloos, *op. cit.,* p. 312. The idea of plastic flow at depth is, of course, as old as that of isostatic equilibrium. This concept was enlarged into one or more active subcrustal currents to which the less plastic, inert surface adjusts itself as best it can by wrinkling and breaking. It was developed systematically by E. Argand in his "Tectonique de l'Asie," *Congr. Géol. Internat., XIII, 1922, Compt. Rend.,* 1er fasc., pp. 171-329. See, e.g., Chap. XII, devoted to the "hydrodynamic analogy," pp. 226-7; Fig. 10 and its explanation, pp. 228-9; then again, p. 267, etc.

and because it fails to explain some of the structures on which it was based by its authors.

Cloos, for instance, quotes the folds of the Swiss Jura Mountains as a good example of wrinkles brought about by subcrustal flow. But very careful and detailed mapping has proved beyond reasonable doubt that the folding of the Swiss Jura Mountains does not extend below the strata of Middle Triassic age.[90] It cannot be ascribed, therefore, to a deep-seated crustal flow capable of "tearing loose" the corner of the crystalline buttress of the Black Forest, as Cloos pictures it.

In the United States, Cloos cites the folds of the Ouachita Mountains as an analogous case. The hypothetical subcrustal flow which is thought to have produced these folds is also supposed to have produced the remarkable belts of échelon faults of Oklahoma[91] (Fig. 73) where it descended to greater depth beneath the surface. Of what magnitude Cloos pictured this subcrustal flow is evident from the way he hints at the possibility that the same current may have reached farther north and east and may have assisted in the folding of the Appalachians.[92]

[90] See pp. 155-6.

[91] A. E. Fath, "The Origin of the Faults, Anticlines, and Buried 'Granite Ridge' of the Northern Part of the Mid-Continent Oil and Gas Field," *U.S. Geol. Survey, Prof. Paper 128-c*, 1920, pp. 75-82; A. W. McCoy, "A Short Sketch of the Paleogeography and Historical Geology of the Mid-Continent Oil District and Its Importance to Petroleum Geology," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 6, 1921, pp. 580-3; Sidney Powers, "Structural Geology of the Mid-Continent Region: A Field for Research," *Bull. Geol. Soc. America*, Vol. 36, 1925, p. 392; Lyndon L. Foley, "The Origin of the Faults in Creek and Osage Counties, Oklahoma," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 10, 1926, pp. 293-300 (with discussion by F. H. Lahee, W. T. Thom, Jr., W. A. J. M. Van der Gracht, W. W. Rubey, and others, pp. 300-3); John W. Merritt and O. G. McDonald, "Oil and Gas in Creek County, Oklahoma," *Oklahoma Geol. Survey, Bull. 40-c*, 1926, pp. 11-35; E. L. Ickes, "Origin of the Faults in Creek and Osage Counties, Oklahoma," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 10, 1926, pp. 727-9; A. I. Levorsen, "Geology of Seminole County," *Oklahoma Geol. Survey, Bull. 40-B.B.*, 1928, pp. 28-39; R. E. Sherrill, "Origin of the En Échelon Faults in North-Central Oklahoma," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 13, 1929, pp. 31-7; W. W. Rubey in "The Geology of Russell County, Kansas," *Kansas Geol. Survey, Bull. 10*, 1930, pp. 72-86; Th. A. Link, "En Échelon Tension Fissures and Faults," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 13, 1929, pp. 627-43 (including discussion!); F. A. Melton, "Age of Ouachita Orogeny and Its Tectonic Effects," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 14, 1930, pp. 57-72 (see also rejoinder by F. R. Clark, *ibid.*, p. 330); L. L. Foley, "Some Applications of the Strain Ellipsoid," *ibid.*, 1930, pp. 231-3.

[92] *op. cit.*, p. 276.

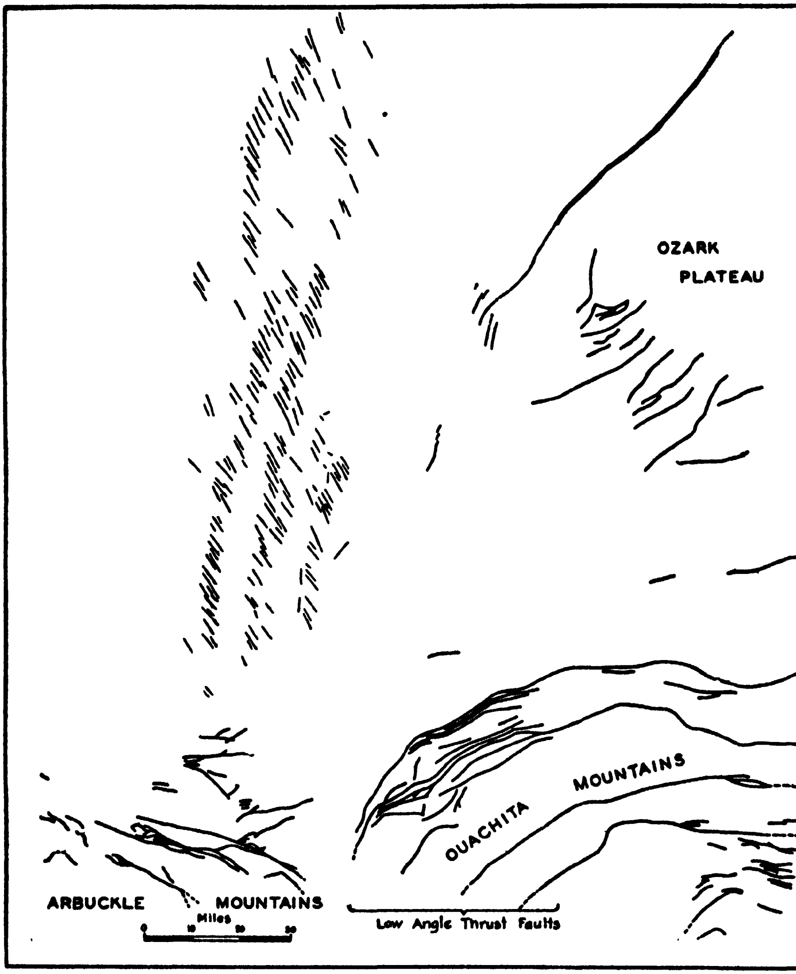


Fig. 73. Tectonic sketch map showing the relation of the *en échelon* fault belts to the Arbuckle, Ouachita, and Ozark Mountains.
(Drawn from the *Geologic Map of Oklahoma*, 1926)

Observations on glaciers, mud flows and granite bodies show that differential flow of a subcrustal current can produce linear belts of échelon fractures. Observation in the laboratory and in the field shows, however, that slight horizontal movement of solid blocks

along a fracture plane will also produce similar lines of échelon fractures in an inert cover of sediment. A good example of échelon fractures produced in the last-named way is found in the traces of the faults along which movement took place during the earthquake of 1906. The reader should consult the corresponding diagrams[93] and photographs of the Earthquake Investigation Commission for an adequate mental picture.

It is, therefore, not necessary to assume subcrustal flow to explain the Oklahoma belts of échelon fractures. The alternative explanation, in fact, was suggested by Fath, who described them for the first time.[94] It implies the existence of north-south trending lines of fracture in the crystalline basement along which slight horizontal differential movements took place which caused the superficial cracking and faulting.[95] Such fractures actually exist in line with these belts, associated with the scarps of the "buried granite ridges."[96]

The deep-seated lines of fracture of which the Oklahoma échelon fault belts are thought to be the surface expression, and those associated with the buried ridges trend approximately at right angles to the Ouachita folds. In this, they are not unique. Groups of normal faults situated in front of folded mountain systems and trending at right angles to them are known from a number of regions. Examples are, for instance, the faults of the Dinkelsberg area in front of the

[93] Figs. 20 and 21, p. 71, in "The California Earthquake of April 18, 1906—Report of the State Earthquake Investigation Commission," *Carnegie Inst. Washington, Pub. 87*.

[94] A. E. Fath, *op. cit.*, 1920.

[95] How superficial and small the displacements are in these échelon faults of Oklahoma may be seen from the following figures: the individual fractures measure only 1½ miles in length on the average and rarely exceed 2 miles. The average throw is less than 50 feet and rarely reaches 100 feet, while the sediments above the Ordovician alone measure from 2,000 to 4,000 feet, the thickness increasing from north to south. The échelon faults, correspondingly, die out above the base of the Pennsylvanian.

[96] See, e.g., R. C. Moore, "Geologic History of the Crystalline Rocks of Kansas," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 2, 1918, pp. 98-112; for a contour map of the buried "Nemaha Mountains," see R. C. Moore and K. K. Landes, "Underground Resources of Kansas," *Kansas Geol. Survey, Bull. 13*, 1927, Fig. 54, opp. p. 72. For faults proved by drilling, see, e.g., John R. Reeves, "El Dorado Oil Field, Butler County, Kansas" in "Structure of Typical American Oil Fields," symposium published by *Am. Assoc. Petrol. Geol.*, Vol. 2, 1929, p. 165. Also A. E. Fath, "Geology of the El Dorado Oil and Gas Field," *Kans. Geol. Survey, Bull. 7* (no date).

Jura folds;[97] the faults of southern Sweden in front of the Hercynian folds of northern Europe; and the (largely buried) faults in front of the Rocky Mountains in Montana, where an échelon belt of fracture occurs which is exactly analogous to those of Oklahoma.[98]

Interpreted in terms of the hypothesis of subcrustal flow, such fractures would run parallel to the line of flow, which is mechanically highly improbable, if not impossible.[99] Here again, therefore, one of the facts on which Cloos bases the assumption of subcrustal flow is distinctly unfavorable to this hypothesis.

7. Lack of Distortional Effects in Forelands and Hinterlands of Arcuate Welts

The échelon faults of Oklahoma show what sort of effect is to be expected in the inert mantle of sediments when the crystalline basement undergoes a moderate amount of distortion. It does not require much imagination to picture what would result from more violent twisting.

Differential movements far greater than those necessary to account for the échelon fault belts of Oklahoma and Montana are being assumed implicitly or explicitly by many students of diastrophism. Every one who thinks that the height of a welt depends entirely or mainly on the amount of shortening at right angles to it, assumes implicitly great differential movements in the forelands or hinterlands or both. The greatest amount of differential strain on the earth's surface outside a certain belt is implied by those who think in terms of the "tectonique en mouvement." Argand's conception of the history of the Alpine mobile belt may serve to illustrate this point (Figs. 74 *a* to *d*).[100]

[97] Cloos interprets these as échelon faults, "Fiederspalten," analogous to the Oklahoma belts. The map does not justify this view.

[98] See *Structure Map of Eastern Montana*, published by U.S. Geol. Survey, 1930; W. T. Thom, "The Relation of Deep-Seated Faults to the Surface Structural Features of Central Montana," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 7, 1923, pp. 1-13; R. T. Chamberlin, "A Peculiar Belt of Oblique Faulting," *Jour. Geol.*, Vol. 27, 1919, pp. 602-13; E. T. Hancock, "Geology and Oil and Gas Prospects of the Lake Basin Field, Montana," *U.S. Geol. Survey, Bull. 691*, 1919, pp. 101-47.

[99] Evidently these fractures as well as the Oklahoma échelon fault belts owe their existence to local adjustments in the crust caused by the pressure which produced the folding and not to the superficial action of thrust masses.

[100] Reproduced from E. Argand, "La Tectonique de l'Asie," *Congr. Géol. Intern. XIII, 1922, Compt. Rend.*, 1er fasc., publ. 1924, Figs. 22-25, pp. 357-9.

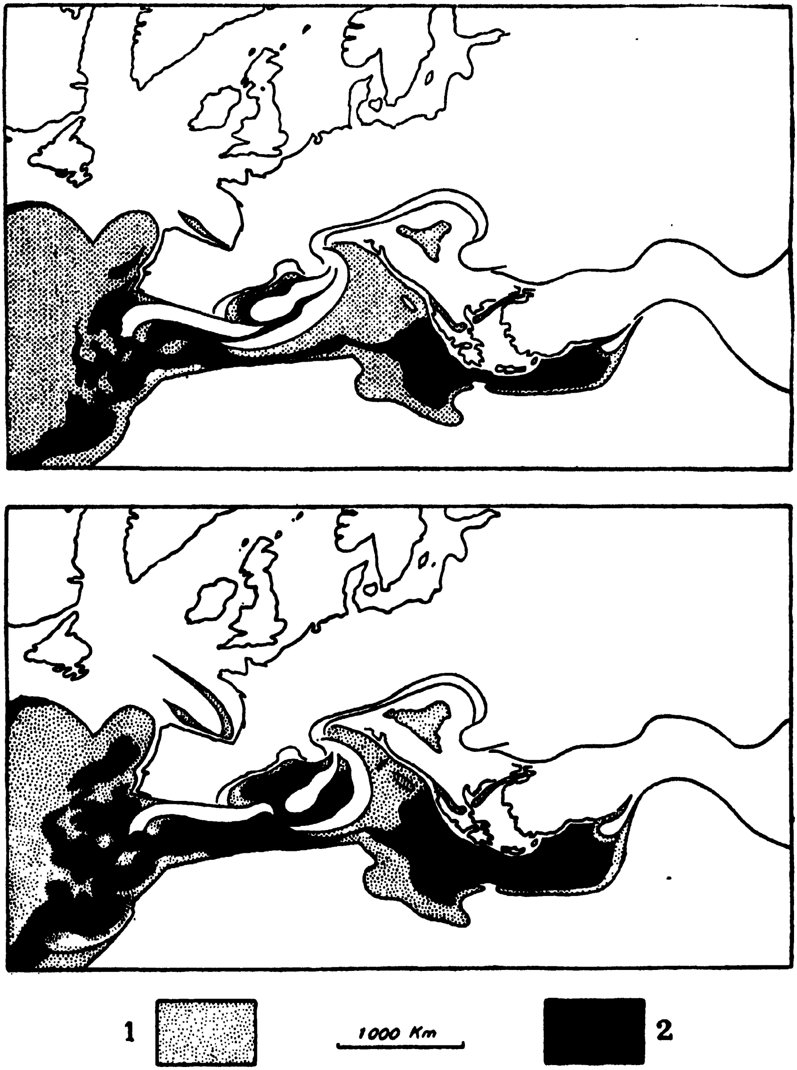


Fig. 74a and *b*

Fig. 74. Four hypothetical maps showing the development of the present configuration of the Mediterranean region according to Argand.

1. (Stippled areas) = regions in which the thickness of the "sial" portion of the crust has been reduced by stretching.
2. (Black areas) = regions in which the sial has become very thin, with or without the formation of holes in which the sima comes to the surface.

(E. Argand, 1922)

Fig. 74c and d

In these figures, four stages of a hypothetical development of the Mediterranean region are shown. In the sense of Wegener's hypothesis, the land areas are thought of as parts of a light outer (sial) layer afloat on the heavy, readily yielding substratum (sima). The land areas are left blank on the maps. The stippled areas represent drawn-out thinned portions of the sial layer, covered by shallow water. The black areas are places where the thinning has reached a maximum forming the deep places of the sea floor where the underlying sima may (or may not) have become visible.

The first of these pictures represents the hypothetical condition of the Mediterranean region during late Oligocene (late Aquitanian) time. It shows an early stage of the pulling apart, the thinning-out of the sial layers, as imagined by Argand. The subsequent pictures show the steps by which this process eventually leads to the condition of Pleistocene time (Fig. 74 *d*) and ultimately to that of today.

To students not familiar with the complicated problems of Mediterranean orogeny, the need for such a revolutionary interpretation may not be apparent. Some such process is almost inevitable if two assumptions concerning Alpine structure are accepted: (a) that the folds of the Alpine system represent the crumpling up of the sediments of a wide space of oceanic dimensions; (b) that all folding was the result of one side of the geosynclinal space overriding its surface in one direction, as a cake of ice overrides the sand of the shore. The back folding in the Alps and comparable structures elsewhere, on that assumption, are late accidental features not connected with the main orogenesis.

If these two assumptions are granted, it is indeed impossible to accommodate the observed mountain structures of the Mediterranean within the irregular curves shown by the present-day map. Argand, therefore, assumes that at the time the folding took place, the Alpine system from the Maritime and Ligurian Alps through the Apennines, Sicily, to the Betic Cordillera and the Rif, formed one continuous chain of essentially east-west trend. This chain of folds was the result of one great thrust movement by which the northern edge or rather a northern promontory of the continent of Africa crept up upon the southern border of Europe. The intricate structure of the Alps is the result of one continent overriding another.[101]

[101] *op. cit.*, pp. 305-6.

This is the hypothetical picture which arose first. It was inacceptable so long as the Apennines with their southeastern trend, or the fine hairpin curve of the Betic Cordillera and the Rif[102] had to be thought of as *in situ*. Either the basic assumptions were wrong or the topography of the Mediterranean region looked different while the major part of the folding was under way. Wegener's hypothesis opened the way for speculations in the latter direction. The maps here reproduced show the solution Argand has suggested. Note how the original zone of Alpine folds breaks into several fragments; how the Iberian peninsula is bent southward until it touches Africa as the distention of the surface causes the sial to tear and to thin, opening up deep basins in the form of "boutonnières," buttonhole-like hollows; how the mysterious subcrustal eddies ("remous") drag ("aspirer") eastward the fragments of the Alpine chain, eddies which form in the wake of the European continent as it drifts northward ("remous de poupe") away from the too obtrusive neighbor to the south.[103] In the course of this movement, the fragments of the Alpine system retain their connection with the European continent. Italy is swept through all the azimuths from southwest to southeast. The south end of Sicily drifts 1,000 to 1,200 kilometers from west to east along the Algerian-Tunisian coast.

This is Argand's picture. It is a grandiose spectacle and a brilliant idea. The writer wishes that he could accept it like the whole of the "tectonique en mouvement." Many things would be so much easier. But before his eyes rises this new obstacle: the absence of any noticeable evidence of the unheard-of distortion which many parts of the Mediterranean lands must have suffered if events had been as Argand pictures them.

Study, for example, the space between the Apennines and the Dalmatian coast as it is represented in Figs. 73 *a* to *d*. In the first picture, this space is occupied by moderately thinned sial, a vast stippled area. As the scene changes to that pictured on the last map in Fig. 74 *d*, this space is reduced to a fraction of its original size. Where does all that matter go? It should be thickened, as the space grows smaller. But no essential new land appears on the map. Now if this were the more

[102] See sheet 36 (A VI) of the *Carte Géologique Internationale de l'Europe*, 1:1,500,000.

[103] Argand, *op. cit.*, p. 307.

mobile sima, through which continents can drift without causing a ripple, this question would be without meaning. But it is merely part of the sial which is stronger by hypothesis. Parts of it lie before our eyes today as, for instance, the flat-lying beds of Cretaceous and Tertiary age which constitute the plateau of Apulia. In what part of the stippled area of Fig. 22 should we look for this bit of foreland? Does any one really believe that any part of the "thinned" sial between the Apennines and the Dalmatian coast could go through the distortions necessary to change the map from Fig. 74*a* to 74*d* and come out unscathed?

If this example seems unconvincing, look at the pivotal area about which the Apennines are supposed to have swung through an angle of 90°. The writer has not available, at this writing, the publications necessary to check the literature on the Ligurian and Etruscan Apennines. But he knows that neither in Suess' work nor in such pertinent writings as he happens to know is there anything to suggest evidence of the sort of strain which rocks in the outermost few miles of the crust would have to undergo if they were twisted in a horizontal plane through an angle of 90°.

Until in the exposed rocks of the Mediterranean region the evidence is found for deformations ascribable to and quantitatively commensurate with the distortions implied in Argand's hypothesis, the writer cannot accept it. The same is true for the relatively smaller distortions that would result if the arcuate portions of welts were the result of differential movements in the surrounding outer crust.

The absence of tangible evidence of differential movements in the plateau lands on both sides of growing welts is thus a fact of sufficient significance to deserve being stated in the form of a law.

Law 26. In most cases, no signs of strong horizontal differential movements are recognizable in the unfolded forelands and hinterlands of arcuate welts.

To the writer, law 26 demands that the curves in the map picture of the orogenic belts were either inherited from the preexisting geosynclinal zones[104] or, if small, arose from secondary stresses within these zones developed under compression.

[104] See also, e.g., F. Löwl, *Geologie*, Leipzig, 1906, p. 172; Albrecht Spitz, "Betrachtung über die Bogenform der Westalpen," *Verh. Geol. Reichsanst.*, Wien, 1919, pp. 247-57.

The reason for the great variation in the intensity of vertical and horizontal movements which is evident in all orogenic zones, must lie within the welts themselves. Opinion 19 seems adequate to explain this variation. According to it, under compression crustal shortening is produced chiefly by the downward expulsion of crustal matter with only a minor upward movement within the uppermost part of the crust. It seems almost inevitable that the proportion of crustal material that is moved upward will vary greatly from point to point, depending partly on minor local variations in the materials of the upper crust, but mainly on the very complicated distribution of stresses within the three dimensions of the mobile zone. This play of greater and lesser differential upward movements is thought adequate to account for the variations in the intensity of deformation from point to point along the axis of a welt without far-reaching horizontal distortions of the crust outside the mobile zone.

No view of the crustal deformation is possible without minor horizontal distortions. The record of these small differential movements is probably found in many of those cases of conjugate jointing in which both systems of joints are essentially vertical. Regional studies of such joints will yield most valuable results, provided they are used discriminatingly in such a way as to give a picture of the stresses that were active from point to point. Statistical methods covering areas are almost valueless. L. Hartmann's analysis of Lüders' lines in terms of lines of stress[105] should serve as a model for such investigations.

8. The Asymmetry of Orogenic Belts

Something remains to be said about the asymmetry of orogenic belts. The facts are generally recognized.

Law 27. The structure of all intensely folded orogenic belts is one-sided, with folding and thrusting outward from the axial welt much stronger on one side than on the other.

Law 28. In arcuate orogenic belts the convex side of the arc exhibits the greater amount of overfolding and thrusting and the stronger marginal folding.

[105] L. Hartmann, *Distribution des déformations dans les métaux soumis à des efforts*, Berger-Levrault, Paris, 1896. See Walter H. Bucher, "The Mechanical Interpretation of Joints," *Jour. Geol.*, Vol. 28, 1920, pp. 709-12.

The first of these two laws simply states what is to be expected under any hypothesis that allows the outer crust to be thrown into welts high enough to feel the effect of gravity. No wrinkle, however formed, would be expected to remain poised in perfect symmetry. As soon as it begins to lean, the bulk of further deformation is transferred to one side.

The second law is more specific. It is possible to imagine ways of producing curved welts in which the tendency would be to lean over toward the concave side of the curve. By way of crude illustration, imagine a board cut along some sharply curved line and the two sides pushed apart so as to leave a curved furrow between them. Let this furrow be filled with some plastic substance to represent a geosynclinal zone. Then let the two sides of the board be pushed together. The plastic mass will rise between them and soon will lean inwards, toward the concave side. Since the sediments of a geosyncline rest in a relatively shallow depression within the earth's crust and not between two blocks, this picture does not apply to them, of course.

According to the view developed in these pages, the welts rise alongside or within the geosynclinal zones at the points where the crust first gives way. As the section of the crust at right angles to the welt shortens, the material of the upper part is forced upward (p. 214). Further deformation within the welt is accompanied by differential movements which influence the process of folding and on the edges of the welt lead to the formation of low-angle thrusts. These thrust planes must extend into the welt as surfaces of contact beween "plastically" flowing bodies of rock. Even in welts which do not show large overthrusts, there must be many such contact surfaces along which the mass of the welt rises differentially.

The presence of numerous such contact surfaces probably accounts for the tendency of curved welts to overfold and overthrust largely toward the convex side of the curve. The direction in which the material of the welt is thrust must be the direction in which there is least resistance. A simple consideration shows that movement from the interior of a welt toward the concave side of the curve meets with greater resistance than movement toward the convex side. In Fig. 75 *A* the heavy line represents the trace of a curved thrust surface intersecting a horizontal plane. The lighter lines show the projection of the thrust plane dipping 20° toward the center of curvature. In

Fig. 75*B*, the projection of a similar thrust plane is shown dipping away from the center of curvature. The customary symbols indicate the direction of dip along these thrust planes. Since movement has to be essentially in a radial direction, the two projections give a measure of the relative areas of the two thrust planes. It is obvious that a similar amount of thrust would require movement along a larger surface, if it were directed toward the concave side. Since friction is directly proportionate to the area involved, it is obvious that thrust planes and planes of contact separating differentially moving bodies of rock will

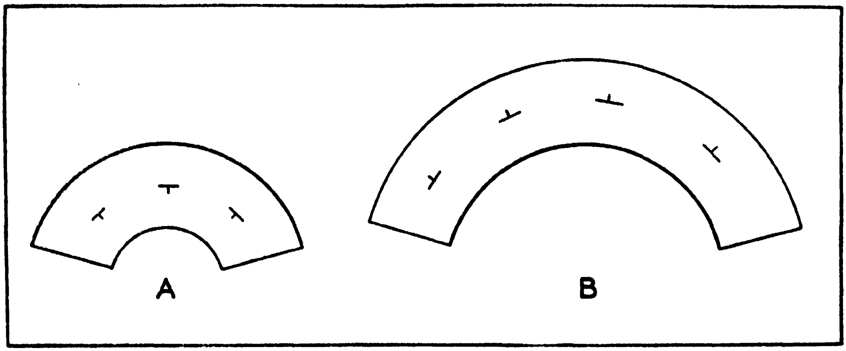


Fig. 75. Ground plan of two shearing planes, *A* and *B*, with semicircular horizontal traces at two levels, the heavier line indicating the higher one which is the same in both figures.

A, dipping toward the center of curvature.
B, dipping away from it.

be directed toward the convex side of the curve where there is least resistance to their formation.

Fig. 75 also shows that movement toward the concave side would cause a crowding of the matter thrust forward. In the opposite direction the matter is made to spread out. Tensional forces arise which disrupt the moving rock mass and thereby reduce resistance to further movement.

The forward urge of individual portions of a welt, the spreading out of thrust masses and even their disruption are inevitable consequences of the mechanics of welt formation here assumed. The "flaws" in the Jura folds and in the Säntis Mountains (p. 245), illustrate the way in which such disruption appears in structure and topography. But they are merely incidents in the formation of very super-

ficial marginal folds. Similar disruptions must take place on a larger scale in the formation of the welts themselves. Whenever the body of a welt is forced up high above the level of the crust, it must be subject to similar longitudinal disruptions at the surface on a correspondingly larger scale. This should be true especially where two arcs join which are convex in opposite directions. On land where erosion and sedimentation continually blur the picture of orogenic changes, the evidence for such disruptions has not been recognized clearly. Observations pointing in this direction have been made, however, in island arcs.

Two observations from the East Indian archipelago are of special interest in this connection. Sumatra and Java are obviously parts of one great line of welts which in the west ties onto the main Burmese axis, and in the east ends in the sharply bent arc of the volcanic islands of the Banda Sea. Yet, when the southeastern end of Sumatra is compared with the western end of Java, two remarkable facts appear.[106] While the tectonic and stratigraphic elements can be matched, in southern Sumatra all folds are overturned toward the northeast, while in western Java they are overturned and overthrust toward the south. In addition, the structural units of these two islands appear displaced horizontally to the extent of several tens of kilometers.

This certainly looks as if the movement in opposite directions had caused the welt axis to tear and to suffer horizontal displacement. The Sunda Strait marks the line of separation. It may actually owe its existence to the disruption.

A similar relation exists between the islands Buru and Ceram at the northern end of the great outer island arc that begins with Sumba and Timor.[107] Buru is part of a small arc convex toward the south, while Ceram constitutes an arc convex toward the north. On Buru, the intensely folded structure is overturned toward the southwest, on Ceram towards the northeast and north. Wanner, in describing this structure,[108] expresses surprise over this contrast in the direction of folding within parts of the same orogenic belt. If law 28 (p. 260)

[106] J. Wanner, "Zur Tektonik der Molukken," *Geol. Rundschau*, Vol. 12, 1921, p. 161.

[107] H. A. Brouwer, "The Horizontal Movement of Geanticlines and the Fractures near Their Surface," *Jour. Geol.*, Vol. 29, 1921, Fig. 8, p. 575.

[108] *op. cit.*, p. 157.

actually holds good, nothing else could be expected. The overthrusting in each case is toward the convex side of the arc.

Here, exactly as in the case of Sumatra and Java, the two islands appear offset one with reference to the other to the extent of several tens of kilometers. And here also, there is a remarkably deep and narrow strait that separates them, the Manipa Strait, over 4,800 meters (16,000 feet) deep. It looks as if the strait were the direct result of the disruption of the welt axis.

The conclusion seems quite inevitable that large tangential displacements have taken place and are perhaps still in progress. But such displacements need not have anything to do with a "drifting" of the islands. The presence of large-scale overthrusting, probably of Alpine character, on Timor[109] has led early to comparing the Malay Archipelago with the Alpine orogeny. Several tens of kilometers is no greater distance than thrust sheets have travelled in all intensely folded orogenic zones. Just such movements are to be expected where thrusting is in progress.

One striking illustration of law 28 deserves special mention. Within the last decade D. Mouchketov and others have shown convincingly that the enormous mountain ranges of central Asia which extend north from the Great Pamir to the Alai Mountains display a rather one-sided structure produced by a force that drove them northward. This is contrary to the widely accepted idea that all orogeny in central Asia was directed radially outward from the "vertex" of Irkutsk toward the periphery—the picture which Suess has drawn so vividly in his *The Face of the Earth* and which underlies Argand's synthesis. Fig. 76 shows the dominant structural trends in this region as drawn by Mouchketov.[110] The great arc of the Pamir mountain system stands out boldly. The fact that deformation was dominantly directed radially outward toward the convex side of this arc constitutes an unusually valuable testimony for the correctness of law 28.

The ranges which lie north of the basin of Kashgar (the western part of the great Tarim basin marked "Kachgarie" on Fig. 76) con-

[109] G. A. F. Molengraaff, "Folded Mountain Chains, Overthrust Sheets and Block-Faulted Mountains in the East Indian Archipelago," *Congr. géol. internat., XII, 1913, Compt. Rend.*, 1915, pp. 691-702.

[110] Reproduced from D. Mouchketov, "Sur la question du grand écrasement de Pamir," *Livre Jubilaire publié à l'occasion du Cinquantenaire de la Fondation de la Société Géologique de Belgique*, 1924. Fig. 1, p. 160.

stitute the mighty system of the Tian Shan. In it overturned folds and thrust faults indicate movement from the north toward the south. Its front ranges have overridden the continental tertiary deposits of the Kashgar basin.

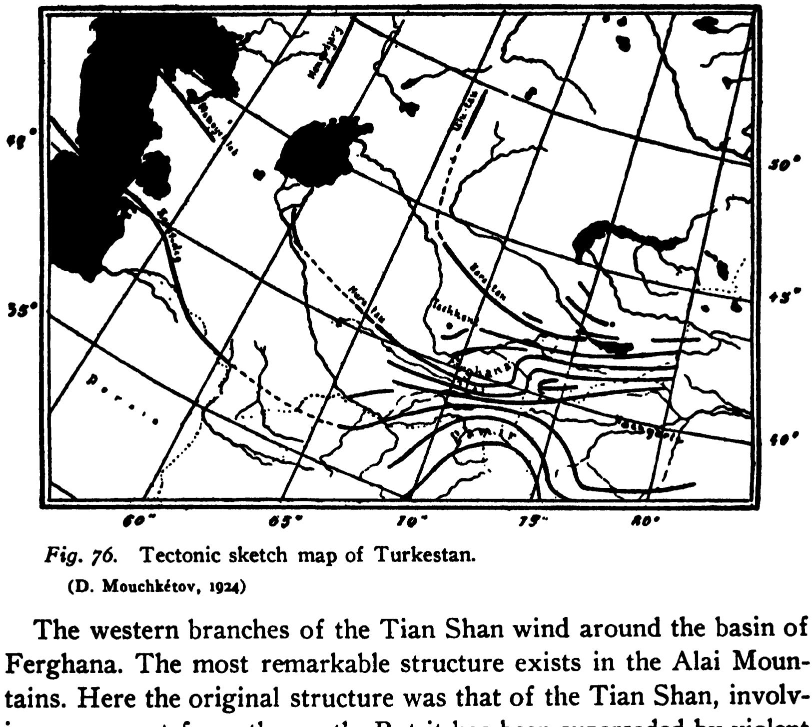


Fig. 76. Tectonic sketch map of Turkestan.
(D. Mouchkétov, 1924)

The western branches of the Tian Shan wind around the basin of Ferghana. The most remarkable structure exists in the Alai Mountains. Here the original structure was that of the Tian Shan, involving movement from the north. But it has been superseded by violent later deformation so that it is now traversed by great thrust planes which dip southward and along which the Paleozoic rocks have been thrust northward on top of Cretaceous and Eocene, presumably at the time of the Pamir folding. That this is primarily due to the presence of the basin of Ferghana may be seen from the areal and structural maps which accompany Mouchketov's beautiful monograph on east Ferghana recently published.[111]

[111] D. Mouchketov, text accompanying Sheets VI-7, VII-7 (East Ferghana) of the *Geological Map of Central Asia* (1:420,000), publ. by the Geologic Committee, Leningrad, 1928 (with elaborate English summary, pp. 213-51).

The diagonal chains of the Ferghana Range which border the Ferghana basin on the east do not show the simple lines of strike drawn in Fig. 76. They show the complicated interference pattern which resulted from the deformation imposed on the old structural lines by the eastern edge of the basin.

Aside from this secondary influence of the two deep basins, then, both the Tian Shan-Alai arc with its convexity turned southward, and that of the Pamir system, with its convexity facing northward, conform to the rule expressed in law 28.

CHAPTER IX

THE INTRUSIVES

Auf eine wie sonderbare Weise doch oft die Natur unseren Voraussetzungen widerspricht!
Eduard Suess, in *Die Entstehung der Alpen,* 1875.

1. The Problem

The reader must have become increasingly aware that the discussion of the structural realities of orogenic belts so far has been very one-sided. Illustrations were drawn chiefly from the Appalachians and the Alps. No reference was made to the Great Basin or the Coast Ranges, and some things that were said do not apply, at least not directly, to the structure of these regions. At the very beginning of this book, the terms "welt" and "furrow" were extended to include fault troughs and their raised margins. They clearly demand special treatment. And not a word was said about magmatic processes, the rôle of intrusives, and of volcanic activity.

The reason for these omissions is equally plain. Extensive normal faulting and igneous activity introduce complications which are absent, at least to a large extent, from such great mobile belts as those of the Appalachians, at least south of the Hudson River, and of the Western Alps. In spite of all local irregularities, mobile belts of this type have behaved as single units throughout their geosynclinal and orogenic phases. The behavior of the Great Basin and California Coast Range belts, on the other hand, has been very different. From the beginning of their history as distinctive orogenic belts, they were divided into numerous minor units which moved more or less independently and thereby introduced a complication of structure entirely unknown in the other type. For the sake of future discussion, we shall designate the former type as "homogeneous" mobile belts, the latter as "heterogeneous" mobile belts.[1]

[1] Schuchert's terms "monogeosynclines" and "polygeosynclines" represent categories based on very different criteria. These, the writer fears, are too vague to be useful. They are furthermore restricted in their applicability by being treated as coordinate with the additional terms "mesogeosynclines" and "parageosynclines" which were coined on purely geographical basis. C. Schuchert, "Sites and Nature of the North American Geosynclines," *Bull. Geol. Soc. America,* Vol. 34, 1923, pp. 195-9.

In the heterogeneous mobile belts, normal faults and volcanic activity play a significant part. If magmatic materials did not appear in the orogenic history of homogeneous mobile belts, we should at once pass on to a systematic discussion of the heterogeneous belts. But they do appear, and they do so with a minimum display of volcanic activity. We may hope, therefore, to find in a study of products of magmatic processes in homogeneous mobile belts a general clue to the relation of orogenic movements and magmatic processes. For, as far as magmatic processes are concerned, volcanism is an accident, just as the formation of fractures is an accident in the larger deformations of the crust.

Turning, therefore, deliberately once more to the homogeneous belts which have served us so well in our analysis so far, we must ask ourselves the question: What factors determine the presence of bodies of liquid rock materials within the crust? It is obvious from our very definition of the "crust" that liquid materials at any given time can only constitute more or less incoherent bodies relatively insignificant in bulk in comparison with the crust at large. The first general statement we can make offers at once an important clue.

2. Basic Intrusives and Geosynclines

Association with furrows.

Law 29 a. Basic intrusive rocks, chiefly in the form of sills and dikes, with or without accompanying effusives, are common constituents of the sedimentary series of "homogeneous" geosynclines.

Law 29 b. There is no corresponding development of acid intrusive rocks in sedimentary series, introduced during the geosynclinal phase.

The first part of law 28 expresses the well known fact that "greenstones" form a widely distributed constituent of great geosynclinal sedimentary series. In the Alps, they occur in large quantities in the Mesozoic sediments (chiefly Middle and Upper Jurassic) of the Pennine *decken* (page 193). They are associated with radiolarites. In the Alps they are called "ophiolites" ("roches ophiolitiques").

Greenstones form characteristic members of various geosynclinal sedimentary series (Mesozoic and Tertiary) along the whole length of the Alpine system, from the Alps and the Apennines, through the inner zone of the Dinaric folds in Bosnia, through Asia Minor and the mighty chains of southern India, through the Burman arc to the

Malay Archipelago and from there northward into the Philippines and Japan, and southward into New Caledonia and New Zealand. On our own Pacific coast we see them beautifully developed in the thick Franciscan series of the Coast Ranges.[2] Here we find them again associated with radiolarian cherts, exactly as in the Philippines or on Celebes and Timor, or in the Alps and the Apennines of Tuscany.

Greenstones are characteristic members of many of the Paleozoic geosynclinal series of Europe, from the Ural Mountains to Scotland. In our Appalachian geosyncline, they are present in the Algonkian Glenarm series (Wissahickon formation of Pennsylvania and Maryland) as amphibolite schists and serpentine and talcose schists. Knopf and Jonas[3] have shown that most of these were originally basic sills and lava flows, in part probably contemporaneous with the greenstone schists of Catoctin Mountain.

We need not go further into the quoting of illustrations. There can be no doubt about the reality of the relation stated in law 28. It is, of course, not necessary that basic intrusives make their appearance in thick geosynclinal series. All the law says is that where intrusions formed during the geosynclinal phase, they are always found to be essentially basic.

Recently Staub, in his arresting book, *Der Bewegungsmechanismus der Erde*, has ascribed an exalted rôle to the "ophiolites" of the great geosynclines. He pictures the thinning of the sial crust along the geosynclines. At its weakest points, the deep-seated magma finds it easy to rise with great rapidity to the surface, too fast to have time to differentiate. He proclaims the ophiolites as rocks representing the parent magma of all other igneous rocks, die "Muttersippe" der "atlantischen" und der "pazifischen" Gesteinsfamilien.[4] There seems no reason for assigning such an exalted position to these "ophiolites." They do not, above all, constitute a unit petrographically. In the Alps the term comprises all sorts of basic rocks ranging from dunite

[2] It is probable that the geosyncline in which the Franciscan series accumulated was of the "homogeneous" type in contrast to the later development of the mobile belt of the Coast Ranges.

[3] E. B. Knopf and A. I. Jonas, "Stratigraphy of the Crystalline Schists of Pennsylvania and Maryland," *Am. Jour. Sci.*, Vol. 5, 1923, pp. 48-9. See also "Geology of the McCalls Ferry-Quarryville District, Pennsylvania," *U.S. Geol. Survey. Bull.* 799, 1929, pp. 60-2.

[4] R. Staub, *Der Bewegungsmechanismus der Erde*, Berlin, 1928, pp. 158-9.

and pikrite through gabbros and diabases to diorite. The term includes especially more or less metamorphosed rocks such as serpentines and amphibolitic schists ("greenstones," "prasinites").[5]

Such a heterogeneous collection of rock types certainly does not serve well as a sample of the parent magma, in competition, for instance, with the plateau basalts.[6] We shall retain the term "ophiolites" for all basic rocks in geosynclines.

It is generally recognized that the plateau basalts rose to the surface along fracture lines of tensional or torsional origin. If it is true that geosynclinal furrows are zones of tensional yielding, it is not surprising that basic magmas generally make their appearance within them, whenever sufficiently continuous fractures or fracture zones extended far enough downward.

The mechanics of the rise of basic magmas. When we speak of lavas welling up along through-striking fractures, we must ask ourselves what it is that causes the magma to rise from the depths to the surface. We have two lines of reasoning to guide us. The first is this: We must not think of the fractures formed under general crustal tension as cutting through the sixty kilometers or miles of the crust in a vertical direction. In the lower part of the crust, where the residual strength of the materials is relatively low, fracturing at right angles to the maximum tensile (principal) stress is unthinkable in view of the weight of the overlying part of the crust. At depth, fracturing under tension is possible solely along planes of shearing. Furthermore, with materials under such confining pressures, the planes of shearing may be expected to intersect in such a way as to form an acute angle in the direction of tension.[7] The normal form of a tension fracture, then, traced from the surface down into the earth's crust may be assumed to be this: It starts either as a vertical or a steeply dipping surface, with the angle of dip decreasing gradually with depth until it reaches a value probably below 30°. There is, of course, not a single fracture generally, but a zone of fractures. Into these the magma finds access from below.

[5] Alb. Heim, *Geologie der Schweiz*, Vol. II, 1921, p. 60.

[6] H. S. Washington, "Deccan Traps and Other Plateau Basalts," *Bull. Geol. Soc. America*, Vol. 33, 1922, pp. 765-804; N. L. Bowen, *The Evolution of the Igneous Rocks*, Princeton, 1928, pp. 142-3, etc.

[7] Walter H. Bucher, "The Mechanical Interpretation of Joints," Part II, *Jour. Geol.*, Vol. 29, 1921, pp. 12-13.

The second line of reasoning deals with the physical conditions of the magma source. The relative uniformity of plateau basalts the world over, both in time and space, from the Algonkian to the present and from Iceland and the Hebrides to Patagonia and from the Deccan to Oregon, can hardly be explained in any other way than that the magma came into existence as a liquid simultaneously with the fissures which allowed it to rise to the surface. There would be evidence of advanced differentiation and resulting greater diversity of petrographic types if this were not true.

Whether the basaltic magma[8] came into existence in the lower part of the crust or at its lower surface is of little consequence here. Nor is the physical condition of the source material of great importance. Daly[9] has given reasons for assuming that beneath the crust there exists a layer of basaltic glass which would be above its melting point, but which is held by the great pressure of the overlying crust in the rigidity which is shown by earthquake records to prevail at greater depths.

Bowen has given strong reasons against this assumption.[10] The most convincing seems to be this. A liquid produced from a basaltic glass, such as postulated by Daly, by relief of pressure would possess a great amount of superheat. Of this the plateau basalts show no evidence. If, on the other hand, the material from which the basic parent magma is derived were a zone of crystalline peridotite, selective fusion would take place upon relief of pressure, producing basaltic liquid interstitially throughout the mass.

Whether we have the instantaneously molten basaltic liquid derived from a glassy layer, or an interstitial liquid within a mush of crystalline peridotite, a force is needed to carry the liquid upward, against gravity, into the crust. This force is provided automatically in the hypothetical view here developed. It is the pressure of the completely mobile (not liquid!) subcrustal body, the same pressure which causes the pulling apart of the resisting crust. In the case of a crystalline peridotitic subcrust, this subcrustal pressure provides the

[8] The systematic chemical differences which exist between the ophiolites of the geosynclines and the plateau basalts are not discussed here. They may indicate essential differences in the avenues of ascent of the magmas or in the relative depth of their origin within the crust.

[9] R. A. Daly, *Proc. Am. Philos. Soc.*, Vol. 64, 1925, p. 283.

[10] N. L. Bowen, *The Evolution of the Igneous Rocks*, Princeton, 1928, pp. 311-15.

filter-press effect by which the interstitial basaltic liquid is separated from the residual crystalline mass. Or, if we accept Daly's hypothesis, it drives on the newly liquefied basalt into the spaces that provide relief of pressure.

The important point is that, according to our hypothetical view, the same stresses which create the relief of pressure along fracture lines also furnish the driving power that carries the heavy liquid up into the light crust. The process as pictured is not such that it is necessary for the magmatic liquid to reach the surface in any quantity. The enlargement of subcrustal space progresses at a secular rate. The crust yields at any time "plastically" rather than by fracturing. Fractures are largely surficial, accidental features. They do not commonly strike through. Yet all the while basaltic liquid finds its way up into the crust, permeating it along many channels, here and there perhaps uniting into larger "reservoirs," breaking through to the surface only occasionally.

Staub's assumption that the great bands of ophiolitic intrusions and extrusions in the geosynclinal belts mark the "axial" lines of these zones of tension may well be near the truth if it is not taken too literally.[11]

Other views. Before leaving this discussion of the great intrusions and extrusions of basic magma, we will do well to contrast the view here developed with the mechanical difficulties that the various theories of continental drift face in them. As a concrete example, read Wegener's account of the separation of Madagascar and India.[12] "It is assumed in our reconstruction that the west coast of India adjoined the east coast of Madagascar. Both coasts consist of a strikingly straight fracture of a plateau of gneiss, which suggests that they could, after the formation of the rift, have slid along one another in a similar manner to Grinnell Land and Greenland. . . . The basalt sheets of the Deccan . . . were formed in the early Tertiary, and

[11] In his book, Staub accepts Suess' interpretation of the ophiolites as abyssal masses introduced during the first orogenic movements. The frequent association of ophiolites with thrust planes may be explained equally well by the weakness and lubricating behavior of serpentinized basic rocks within a part of the crust undergoing deformation. Corresponding serpentinized masses exist, for instance, in large numbers in the undisturbed Cretaceous sediments of the Gulf Coastal Plain.

[12] A. Wegener, *The Origin of Continents and Oceans,* translated from the third German edition by J. G. A. Skerl, New York, 1924, pp. 62-3. (The italics are the writer's.)

therefore may be *brought into causal connection with the detachment*." Wegener's maps[18] show that in early Tertiary time Wegener pictures the separation of India and Madagascar as only barely begun. Madagascar is still a part of Africa. We then have the picture of the two continental floats pulling apart, drifting on the heavy basaltic substratum of the oceans. As they separate, some of the substance of this substratum is forced up at least two miles above the surface of that level on which the continents float. How is it done? What exactly is meant by the sentence that the outpouring of the Deccan basalts "may be brought into causal connection with the detachment"? We may picture to ourselves water raised above the level of the sea in the cracks of an iceberg or splashing over its front as it rides the waves. But nothing comparable is thinkable when the speed of the process is cut down to one-thousandth or one-hundred-thousandth of that of the simile. Frankly, the phrase "into causal connection with the detachment" appears to the writer entirely without meaning. But perhaps an interpretation could be found easier than for such mechanical difficulties as getting the front edges of the more rigid floats thrown into permanent wrinkles by the pressure against a medium of suspension which yields to the advance of the floats without a recognizable ripple. It is at least worth while to keep such minor difficulties in mind while formulating an opinion as to the usefulness of a hypothesis in leading to an understanding of the concrete details of geological structure.

The second part of law 28 expresses a general fact which is borne out by the same regions which testify to the truth of the first part. Just as basic intrusives intruded during the phase of sedimentary accumulation are conspicuously present in thick geosynclinal sediments, so acid intrusives are conspicuous by their absence. They clearly follow different laws both as to the place and the time of their appearance in the outer part of the crust, within reach of erosion. This is expressed in the next three laws.

3. Acid Intrusives

Three laws.

Law 30. As far back as the nature of the existing geological record permits us to judge, the larger bodies of acid intrusives have approached close to the earth's surface along belts of orogenic folding.

[18] See Fig. 16 of this book, p. 75.

Law 31. In all strongly asymmetrical orogenic belts they lie eccentrically on that side from which the folding pressure acted.

Law 32. By far most acid intrusives cut across the structures produced by the folding pressure in such a way as to indicate that they arrived after the folding but so shortly after that they must bear a genetic relation to the orogenic phase.

Association with welts. Until the 'seventies of last century, law 30 would have been stated in a form appropriate to the volcanistic theory of J. Hutton and L. von Buch. "Granites" appear in the central axes of folded mountains with such regularity that it was inevitable that they should have been placed into genetic relation to the folding after their igneous nature had been realized. The idea that the hydraulic pressure of the acid intrusives of the "central massifs" had created the mountains was found untenable only when field observations and stratigraphic analysis had reached the degree of refinement which made accurate timing of the events of folding and intrusion possible. In most cases it became evident that the intrusive rocks are much older than the process of folding. In 1875, E. Suess demonstrated in his *Die Entstehung der Alpen* for the first time convincingly that the intrusive rocks of the central axis are of Paleozoic age and have been involved passively in the orogenic deformation that made the Alps as we know them. His conclusions were borne out completely by the masterly observations of A. Heim and the large number of distinguished Alpine geologists. Yet so difficult are the problems of timing involved that to this day even in the Alps the controversies have not come to an end. The views of Weinschenk, Klemm, Rothpletz, and others who thought they had found evidences of Mesozoic or even Tertiary age of some of the granites in the Pennine Alps continue to be quoted. But it seems that not one of the men who have done intensive areal mapping in those regions recognizes them as valid. This emphasizes the difficulties inherent in the question of the age of intrusions and the need of detailed work in many critical regions.

The situation in the Alps is duplicated in most other regions. The last to ascribe to intrusive magmas a major active rôle in the making of mountains are W. Penck and Salomon.[14] He was led to this view by the mapping (on the scale 1 :200,000) of the high and difficult moun-

[14] See, e.g., Walther Penck, "Zur Hypothese der Kontinentalverschiebung," *Zeitschr. Ges. f. Erdkunde*, Berlin, 1921, pp. 130-43; W. Salomon, "Magmatische Hebungen," *Sitz. Heidelberger Akad. d. Wiss.*, 1925. Abh. 11.

tain ranges at the south and southeast side of the Puna de Atacama in northwest Argentine. He interpreted the granites and associated effusives of early Mesozoic age as the initiators of the major folds which were to develop into the later final mountain structures.[15] But H. Gerth has since brought forth what seem to be cogent reasons[16] to show that at least the bulk of these granites considerably antedates the time of the major folding for which Penck held it responsible.

In the United States, Keith has recently expressed the opinion "that igneous intrusions, which are the greatest examples of heat and force known to us, and which are definitely associated with mountain-building, should be rated as the cause of the building of mountains."[17] He points especially to the increase in the number of "post-Carboniferous" granite areas in back of the structural salients along the western front of the Appalachians. In his presidential address, five years later, he ascribed to "their forcible intrusion . . . the excess thrust toward the northwest at the salients."[18] The only evidence for such a causal connection is just this statistical relation which is shown by his map[19] or by Willis and Stose's "Geologic Map of North America."[20] But since the salients of the mountain front also coincide with the regions of greater relative uplift of the older crystalline portion of the Appalachians, the larger number of granite exposures may be due merely to deeper erosion. To prove a causal connection we must turn to better evidence.

Eccentric position in asymmetric welts. The "post-Carboniferous" intrusions of the Appalachians constitute also a fine example of the kind of relation which is comprised by law 31. On an earlier page (pp. 174-81) we have analyzed the major elements of Appalachian structure south of the Hudson River: The outer belt of folded and thrust-faulted essentially unmetamorphosed sediments; the crystalline

[15] Walther Penck, "Der Südrand der Puna de Atacama: Ein Beitrag zur Kenntnis des andinen Gebirgstypus und zu der Frage der Gebirgsbildung," *Abh. Sächs. Akad. Wiss., Math.-phys. Kl.*, Vol. 37, Leipzig, 1920.

[16] H. Gerth, "Die Bedeutung der geologischen Erforschung des Südrandes der Puna de Atacama für die Geschichte der Anden und die Gebirgsbildung im allgemeinen," *Geol. Rundschau*, Vol. 12, 1922, pp. 320-40, esp. p. 333.

[17] A. Keith, "Outlines of Appalachian Structure," *Bull. Geol. Soc. America*, Vol. 34, 1923, p. 335.

[18] A. Keith, "Structural Symmetry in North America," *Bull. Geol. Soc. America*, Vol. 39, 1928, p. 350.

[19] 1923, Pl. IV, opp. p. 309.

[20] 1:5,000,000, 1911, in *U.S. Geol. Survey, Prof. Paper 71*, 1912.

welt ("anticlinorium") of the Blue Ridge; and finally, a great eastern mass of crystallines bounded on the west side by the Martic overthrust. We can judge the validity of law 31 when applied to this region only as far as the last orogenic epoch is concerned. For earlier epochs accurate time determinations are lacking. But the intrusives of the last epoch show by their relative freedom from metamorphism that they have never been subjected to orogenic stress.[21] They are the "post-Carboniferous" granites of current literature. Their distribution has been summarized recently by A. I. Jonas.[22] In the northern portion of the region concerned, that is, from Pennsylvania to central North Carolina, the scattered "post-Carboniferous" granites occur only in the easternmost of the tectonic units, the "Martic thrust block." From central North Carolina south into Georgia, they overlap into the eastern part of the Blue Ridge welt (the Whiteside granite). This is the typical one-sided distribution of acid intrusives in strongly asymmetrical orogenic units confined entirely to that side from which the orogenic pressure came.

The same relation is shown by the late intrusives in the Alps. Only within the last two decades or so has work of sufficient detail been done to demonstrate beyond doubt that there are a few intrusive masses in the Alps which came after the last great epoch of folding. They show no signs of dynamic effects either in their own crystalline texture or in the abundantly exposed zones of contact metamorphism. In this relation they are the exact counterpart to our Woodstock granite of the vicinity of Baltimore or the Petersburg granite of Virginia within the intensely folded crystalline Appalachians.

Now note the distribution of these young (Tertiary) intrusives in the Alps.[23] Several isolated smaller stocks occur near the southern border of the Alps between Ivrea and Lago Maggiore: the diorite of Traversella northwest of Ivrea and a similar stock north of Biella, both within the "zone of roots," and the granite of Baveno within the Insubrian zone. Then, east of Bellinzona, a belt of granite intru-

[21] Of early discussions see, e.g., those by G. H. Williams and C. R. Keyes, "The Origin and Relations of Central Maryland Granites," *U.S. Geol. Survey, Fifteenth Ann. Report,* 1895, pp. 651-740.

[22] A. I. Jonas, "Structure of the Metamorphic Belt of the Central Appalachians," *Bull. Geol. Soc. America,* Vol. 40, 1929, pp. 503-13, esp. pp. 511-13.

[23] See Rudolf Staub, "Tektonische Karte der Alpen," 1923, 1:1,000,000 in *Beitr. z. Geol., Karte d. Schweiz,* N. F. Lieferung 52.

sions that follows the "zone of roots" and expands at its eastern end into the great "Bergeller massif," which lies south of the Valle Bragaglia (Bergell). On von Bubnoff's sketch map (our Fig. 48, p. 182) it is shown in solid black like the other post-folding intrusives and bears the letter *D*.[24] This granite mass cuts across the southernmost part of the great recumbent folds of the Pennine region. Farther to the east lies the great Adamello intrusive of tonalite (quartz-diorite), marked *Ad* on the map, Fig. 48. Still farther east, in the dolomites of South Tirol, lies the petrographically remarkable stock of Predazzo. This is not shown on the map, Fig. 48. Other areas which von Bubnoff has represented as belonging to these latest intrusions are of doubtful age.

All these "post-Alpine" intrusives are confined to the southern part of the Alps, entirely in accord with law 31. They are, moreover, not limited to any one of the major structural units. They occur not only within the zone of "roots," that is, of vertical isoclinal folds, but also far south of it in the "Dinaric" portion of the Alps and in one case, at least, they cut through the recumbent folds to the north of it.

It is interesting to speculate what this southern, "Dinaric" part of the Alps would look like if we could strip it of its thick mantle of Permian and Mesozoic sediments. In his recent valuable book on *Intrusionstektonik und Wandertektonik*, F. E. Suess[25] suggests that if erosion were to expose the deeper substructure of this "stoss-side" of the Alps, one might well find the post-Alpine granites expanded and more or less united into a great network of intrusions. The picture might not be unlike that of the post-Carboniferous granites of the southern Appalachians of North Carolina and Georgia.

In the Variscan orogenic belt of Europe, the zone of dominant intrusives is broadly developed along its southern border as, for instance, in the larger southern part of the Bohemian massif, the Black Forest, the Vosges Mountains, and in the southern portion of the Central Plateau. Here the intrusions were the last structural event.[26] The structural features produced by the preceding deforma-

[24] The Monte della Disgrazia, to which the letter refers, lies outside the granite intrusive.

[25] F. E. Suess, *Intrusionstektonik und Wandertektonik im varissischen Grundgebirge*, Berlin, 1926, pp. 237-8.

[26] F. E. Suess, *op. cit.*, p. 6.

tion have been more or less superseded by those which resulted from the intrusion.

This zone of dominant intrusives is followed on the north by a belt of *decken* structure comparable to that of the Pennine Alps. It has been recognized clearly so far only in the complicated structure of the Erzgebirge, which separates the province of Saxony from Bohemia.

Still farther north follows the intensely folded series of unmetamorphosed sediments of the "Ostthüringer Schiefergebirge." This, in turn, is but a part of the great Variscan geosyncline which, intensely folded and thrust-faulted, extends from the Taunus Mountains to the Ruhr and across the Rhine into the Franco-Belgian coalfields.[27]

Here again we find the same relation. The great intrusives are found in largest numbers outside the Variscan geosynclinal belt crowded together on the side from which the active mountain forming pressure came. Some have been intruded into the older part of the folded sediments as far north as the Harz Mountains. But none has entered the thick series of the youngest coal-bearing beds.

F. E. Suess states explicitly that there has been a progressive shifting of the intrusions from the southeast toward the northwest. As the zone of active folding was displaced toward the northwest in successive orogenic epochs, it was followed by a belt of intrusions. The intrusions always appeared after the orogenic spasm and always on the side from which the pressure acted. Suess says it is as if the cooling intrusions caused the crust to stiffen and to squeeze out magma along its front when folding is renewed.[28]

In America it is not possible to speak of acid intrusives in connection with orogeny without referring to the great "batholiths" of the west. There, however, subsequent events have partly dismembered the earlier orogenic units and partly concealed them beneath lavas and alluvial waste. In the Sierra Nevada we cannot even be certain that we remain within the self-imposed limits of "homogeneous" mobile belts. Nor do we possess enough detailed observations tied together in the field, to speak in terms other than mere suggestion. Yet we can with such qualification arrive at a general statement that seems

[27] Lozinski inferred such an asymmetric position for the Variscan as well as numerous other orogenic zones of volcanism. See W. V. Lozinski, "Vulkanismus u. Zusammenschub," *Geol. Rundschau,* Vol. 9, 1919, pp. 65-98.

[28] F. E. Suess, *op. cit.,* p. 247. But Suess speaks in terms of "Wandernde Schollen."

to be reasonably correct if we limit ourselves to one section of the orogenic belt which shared roughly the same general history preceding the Nevadian orogenic epoch. As such we choose the portion which lies between the parallels 37° and 43° N.

Within this belt we find the easternmost orogenic unit in the western Great Basin. It is characterized by the unmetamorphosed condition of its late Paleozoic and earlier Mesozoic sediments thrown into relatively moderate folds more or less overturned toward the east, as in the Humboldt Mountains, and perforated by granitic intrusives. The granitic intrusions increase in importance westward and reach their maximum in the eastern Sierra Nevada. Throughout the Sierra Nevada the thick late Paleozoic, Triassic, and Jurassic series lie compressed into nearly isoclinal folds which are typically overturned toward the west with their axes dipping eastward toward the zone of acid intrusions. Even the most casual inspection of the fine series of early folios covering the Sierran gold belt impresses one with this fact which is so inconvenient to anyone who would like to construct a symmetry between the Atlantic and Pacific sides of the continent. In the Klamath Mountains the imbricate structure, which one can only surmise in the intricacies of Sierran structure, is very evident with the great thrust planes dipping toward the east and with the older rocks thrust on top of the Franciscan radiolarites.

The larger western part of the Nevadian mountain folding lies buried beneath younger sediments. Scattered fragments stand as isolated fault blocks in the Coast Ranges. Here the radiolarites and basic igneous rocks play a conspicuous rôle. A part of their folding and the shearing in the accompanying greenstones represents deformation caused by the Tertiary epochs. Originally their structure was probably such as is typical of the marginal folds in which the orogenic force dies out away from the active welts.

This hasty sketch may suffice to show that here also the zone of dominant acid intrusions lies asymmetrically on one side of the orogenic zone and precisely on that side from which the folding pressure acted.

Discordant relation of folds and schistosity. Turning now to law 32, we may use one illustration from the Sierra Nevada as represen-

tative of all the others referred to above. Fig. 77[29] is reproduced from Turner's description of the Bidwell Bar quadrangle in the northern Sierra Nevada. The schistose rocks shown on the map comprise the sediments of the Calaveras formation and bands of amphibolites and serpentines derived from basic tuffs and lava flows or sills. The areas

Fig. 77. Diagrammatic geologic map of the Bidwell Bar quadrangle in the Sierra Nevada, California, showing the relation of the massive granitic areas to the planes of schistosity of the metamorphic rocks.

(H. W. Turner, 1898)

[29] Reproduced from H. W. Turner, "Bidwell Bar Folio," *U.S. Geol. Survey, Folio 43,* 1898, Fig. 1, p. 6.

marked with close-fitting divergent hachures represent massive basic rocks associated with the sedimentary series, chiefly massive amphibolites and serpentines with remnants of peridotite, pyroxenite, etc. The white areas with divergent hachures represent the late acid intrusives, chiefly granite, granodiorite and quartz-diorite. The conspicuous fact shown by this sketch is that the granite intrusives did not produce the schistosity but found and utilized it in their ascent. This is shown in the eastern and southeastern part of the map by the independent manner in which the belt of schists enters the area away from intrusives and then by the way the masses, especially the southernmost of them, cut across it. In the northwestern half of the map, at first sight, it looks as if the schistosity were the result of the intrusions, by the manner in which it seems to wrap around them. But a glance at the areal geological map in the folio shows at once that it is not merely schistosity that curves more or less around the intrusive but the whole rock series with its alternating beds of sediments and amphibolites and serpentines. It is the body of the intrusive adapting itself to the strike of the rocks or at best forcing the rocks aside which this map picture shows. Even where there seems to be on the whole good parallelism between the edge of the intrusive and schistosity, the intrusive is seen cutting across the lines of schistosity in detail. Hunter saw this clearly and concluded "that the schistosity in the main was developed at a period antecedent to the granitic intrusions."

This is not the place to enter into the necessary stratigraphical details to illustrate the nature of evidence from which law 32 is derived. We may accept the testimony of outstanding students of intrusions. Daly writes: "Without known exception, each batholithic invasion has followed more or less closely a period of strong crustal deformation affecting the older formations of the same region. This rule, which seems really to have attained the dignity of a law, is generally recognized by geologists but no one has hitherto published a statement showing how full is the evidence."[80] Daly condenses the evidence into a valuable table. Cloos expresses the same law in this form:[81]

[80] R. A. Daly, *Igneous Rocks and Their Origin*, New York, 1914, p. 96.

[81] H. Cloos, "Bau und Bewegung der Gebirge," *Fortschritte d. Geol. u. Pal.*, Band VII, Heft 21, Berlin, 1928, p. 316. (The word "plutone" means "intrusive.")

"Die Plutone sind hier fast ausnahmslos jünger, *aber nur sehr wenig jünger* als die Gebirgsbewegung, mit der sie hochkommen."

With these three laws before us we can now ask ourselves what the causal relation may be that connects orogenesis and acid intrusions. Their grouping together on the side from which the folding pressure acted has led repeatedly to the suggestion that their intrusion furnished the pressure that caused the folding. But wherever exposures permit us to form an opinion we always find the structural lines already in existence when the intrusive arrives. It is as if we tried to blame a line of bolts driven through a number of superimposed corrugated iron sheets for the wrinkling of the sheets. No, the genetic connection must be of a less direct sort.

Let us first ask ourselves, just how far the dominant field relations of the larger acid intrusives warrant the widespread assumption that they were driven into their final lodging places by orogenic pressure. Two laws offer important information. These we shall discuss, one at a time.

Thin roofs.

Law 33. Large discordant acid intrusives are capable of penetrating the crust to points very near the surface without bursting the roof in catastrophal fashion.

This general fact is well enough known but, like others, too little appreciated in its implications. The Boulder batholith, for instance, which covers an area of some 1,100 square miles, carries on its central portion remnants of the roof beneath which it came to rest. They consist of large areas of andesite and latite breccias, tuffs, and lavas.[32] These constitute the latest rocks which had been laid down unconformably on the folded rocks of the region, after a period of considerable erosion. They can only have measured a few thousand feet in thickness. Yet the granite magma (quartz monzonite) rose from the depths into this outermost of the rock layers in this region.

The great granite batholith of the Lausitz region in Saxony, between Dresden and Görlitz, which comprises almost 5,000 square kilometers (1,900 square miles), bears a similar relation to its roof.

[32] See map in A. Knopf, "Ore Deposits of the Helena Mining Region, Montana," *U.S. Geol. Survey, Bull. 527*, 1913, Pl. 1, opp. p. 20. For an excellent concise description see Paul Billingsley, "The Boulder Batholith of Montana," *Trans. Am. Inst. Mining Eng.*, Vol. 51, 1916, pp. 31-56.

It penetrates Mississippian (Kulm) rocks,[83] being itself of Pennsylvanian age. The roof can hardly have been thicker than about 3,000 feet.[84]

In southwest Africa, northeast of Swakopmund, Cloos[85] found the granite batholith of the Erongo Mountains cutting through the folded bedrock series into the surficial flows of porphyrites which form a thin veneer over the surface, just a few hundred meters thick.

Preservation of roof structure.

Law 34. Where remnants of the roof of a large discordant intrusive have escaped erosion they are found to have preserved the structural relation to their surroundings which they had before the advent of the intrusive.

This peculiar behavior of roof pendants is shown on the map of the batholith in Bidwell Bar quadrangle, California, of our Fig. 77. In the original, the larger of the two prongs which extend in a northwesterly direction into the southern larger granite mass is seen to consist of three zones: Amphibolite, Serpentine, and Sediments of the Calaveras formation. All three zones are continued on the northwest side of the granite swinging into an east-west strike. This is not reflected in the pattern of the map here reproduced which shows only the trend of schistosity, not the boundaries of formations.

But much better illustrations may be found in many regions of granitic intrusions. In his description of the Boulder batholith, Billingsley writes: "Large areas of folded and faulted rocks are gone, and their place is occupied by granite, but the change has left no record of dynamic disturbance of the antecedent structure. The top of the granite—at the high points of the dome—reached the andesite series, which at that time rested upon the bevelled edges of the folded sediments. At lower points a varying thickness of the tilted rocks intervened, and in places . . . fragments of sedimentary rock remain between the granite and the andesite. These beds retain the

[83] See the new "Geologische Übersichtskarte von Sachsen," 1:400,000, by F. Kossmat and K. Pietzsch, *Sächs, Geol. Landesamt,* Leipzig, 1930.

[84] H. Cloos, "Das Batholithenproblem," *Fortschritte d. Geol. u. Pal.,* Heft 1, Berlin, 1923, p. 31 (also p. 12).

[85] H. Cloos, "Der Erongo, Ein vulkanisches Massiv im Tafelgebirge des Hererolandes und seine Bedeutung für die Raumfrage plutonischer Massen," *Beitr. z. geol. Erforsch. d. deutsch. Schutzgebiete,* Heft 17, Berlin, 1919.

structure of the early folds, and the sloping beds are truncated by the granite below."[36]

H. P. Cushing, in his description of the pre-Cambrian rocks of the Thousand Islands region, gives a graphic account of the roof pendants in the Picton granite, "the latest, most extensive, most interesting, and most important of the intrusives of the region." He writes: "While mapping Wellesley and Grindstone Islands it quickly caught our attention that the abundant inclusions with which the Picton granite is everywhere charged were arranged in belts, that is, along a given line the inclusions were all quartzite, along an adjoining line they were all amphibolite, along another nothing but granite gneiss inclusions appeared. . . . Our strikes and dips, read on the rocks in the field, gave absolutely concordant results as we passed from one inclusion to another, results also concordant with the readings obtained on the same rocks beyond the reach of the intrusions. We were able to map the original belts of Grenville quartzite and schist, and the intrusions of Laurentian granite gneiss, as accurately as though the Picton granite was not present, so little had they been disturbed by the intrusion."[37]

On the east slope of the southern Sierra Nevada, Knopf has mapped a roof pendant of schist which runs like a narrow wall, only a few hundred feet wide, as an offshoot from a larger mass for a distance of over four miles through the granite. In the Middle Fork of Bishop Canyon, it is exposed over a vertical range of over twenty-five hundred feet. He writes: "The remarkable attenuation of the northward extension of this roof pendant and its linear persistence despite its extreme narrowness are very notable, and this and like features elsewhere in the region lend strong support to Daly's contention that batholithic invasion is not accompanied by disturbance of the tectonic axes of the invaded rocks."[38]

Similar thin wall-like remnants of the roof rock are frequently observed on a smaller scale. Thus Balk describes two bodies of gran-

[36] Paul Billingsley, "The Boulder Batholith of Montana," *Trans. Am. Instit. Mining Eng.*, Vol. 51, 1916, pp. 39-40.

[37] H. P. Cushing, "Geology of the Thousand Islands Region," *New York State Mus., Bull. 145*, 1910, p. 43.

[38] Adolph Knopf, "A Geological Reconnaissance of the Inyo Range and the Eastern Slope of the Southern Sierra Nevada, California," *U.S. Geol. Survey, Prof. Paper 110*, 1918, p. 62. See esp. the geological map, Pl. 1. The schist pendant is seen at the westernmost point of the map.

ite, one and one-half miles northeast of Woodbury, Vt., which are intruded into steeply dipping phyllites. They are separated by a thin septum, only two yards wide, which consists of phyllite in the form of a sharp anticline, retaining the strike of the adjacent phyllite series.[39]

Mechanics of the rise of discordant acid intrusives. Thus most, if not all, "latest" intrusions in regions of orogenic folding give evidence of having reached their ultimate positions by changing places in some way with the solid material above them, after the orogenic stress had thrown the sedimentary mantle into folds and had endowed it with schistosity. Daly's keen analysis has given us the concept of overhead stoping. In reviewing Daly's papers,[40] Salomon emphasized that as far as the mechanism of intrusion is concerned the essence of his views lies in the concept of magma and solid rock changing places.[41] All other ideas connected by Daly with stoping, such as the power of the magma of shattering the rock with which it is in contact, are independent and of secondary importance. Cloos saw that little progress in understanding the space problem of magmatic intrusives could be hoped for without additional accurate information. He created the field of detailed "granite-tectonics" and with his fine enthusiasm won a body of capable students who have contributed under his leadership a series of valuable detailed studies of the inner structure of granitic intrusions.[42]

These investigations have shown that the details of texture and structure of the intrusives reflect the last movements of the magma immediately before solidification. And the lines of movement often betray the shape of the moving body of magma. This, Cloos could show, is by no means always that of a huge plug with nearly vertical

[39] Robert Balk, "A Contribution to the Structural Relations of the Granitic Intrusions of Bethel, Barre, and Woodbury, Vermont," *Fifteenth Biennial Rept., Vermont State Geologist*, 1925-1926, pp. 42-3.

[40] *Am. Jour. Sci.*, 4th ser., Vols. 15 (1903), 16 (1903), 26 (1908).

[41] He called Daly's view "Platz-austausch" hypothesis. This term has since gained currency among German-speaking geologists. See W. Salomon, "Über Magmatische Vorgänge," *Geol. Rundschau*, Vol. I, 1910, Besprechungsen pp. 8-18, esp. p. 13.

[42] For a bibliography of papers by Cloos and his collaborators, see Robert Balk, "Primary Structure of Granite Massives," *Bull. Geol. Soc. America*, Vol. 36, 1925, pp. 695-6. Of the papers there listed, one deserves special mention: H. Cloos, "Das Batholithenproblem," Berlin, 1923. A discussion of the batholith of the Sierra Nevada is contained in H. Cloos, "Bau und Bewegung der Gebirge," *Fortschritte d. Geol. u. Pal.*, Band VII, Heft 21, Berlin, 1928, pp. 5-23.

sides such as we see exposed in some of the tall canyon walls of the Sierra Nevada and the mountains of British Columbia. Many European examples of what seemed typical batholiths proved to be rather thin sheets cutting unconformably across the folded structures. In such cases, it looks as though the magma, on its way up from below, had caused a plate bounded by such preexisting low-angle fracture planes to settle, allowing the magma to rise above it. This process is imaginable on a very large scale causing huge plates to change places with the magma, as was suggested, for instance, in a diagrammatic way by Iddings.[48]

The other extreme is represented by the more or less circular bosses and stocks that could not have created the chambers they occupy in any other way than by localized "overhead stoping." Between these two extremes lies the multitude of forms of the discordant acid intrusives from thin, nearly horizontal plates to thick, irregularly angular or rounded bodies.

The larger field relations, then, as well as the detailed inner structure and texture of the discordant granitic intrusions show conclusively that they have come within reach of observations at a time when most of the deformation of the sedimentary mantle had been accomplished by the orogenic stress. On the other hand, Cloos' detailed studies have proved that the regional stress had not completely ceased while most granitic intrusive bodies studied by him rose to their final lodging place. He could show that generally the direction of the "stretching," that is, the direction of drawing out and thinning out of the solidifying magma recorded by the parallel orientation of linear elements among the crystals and inclusions, is quite independent of the irregularities of shape of the intrusive body. This remarkable uniformity in the inner texture of the discordant intrusive masses seems to be a universal property. It must be due to the regional stress which ultimately caused and controlled the discordant rise of the magma. In most cases this regional stress has the same direction as that which produced the last folding. Even the normal shearing and tension cracks and the dikes which occupy them bear a definite relation to this regional stress.

[48] J. P. Iddings, *The Problem of Volcanism,* New Haven, 1914, pp. 204-13, esp. Fig. 61, opp. p. 208.

The physics of aggregates consisting of a solid suspended in a liquid phase, have recently been discussed in a most illuminating way by Mead.[44] He shows that when in the process of cooling the solid phase has become so predominant that the grains are no longer free to move but interfere with one another when the mass is deformed, change of shape is possible only with expansion in bulk. This condition is called dilatancy. Such a mass, although containing perhaps 10, 20, or even 30 per cent liquid, is capable of fracturing. Such are the fractures in granite which bear a definite relation to the last plastic yielding of the intrusive. Into the earlier fractures, which formed while some of the liquid phase still existed, the liquid parts oozed, which in general were more acid and richer in mineralizers than the main body of rock. Hence the pegmatitic and aplitic dikes which occupy fractures definitely oriented with reference to the regional stress.

Looking back over the large field so hastily sketched, we arrive at a picture something like this. In some way the granitic magma must come into existence under the action of the stress which causes the earth's crust to shorten along the mobile belts, and to be thrown into folds along the surface which grow in intensity as the major welts rise upward and outward. On page 214 we arrived at the opinion that in this process of crumpling the larger part of the crustal column which undergoes compression is forced downward into the shrinking subcrustal space. We have shown that in this process of compression there is much differential flowage even within the accessible outermost part of the crust. Flowage, involving a great deal of molar besides molecular movement, must dominate deformation in the deeper parts of the crust. This must produce heat. It seems reasonable to assume that in some zone, not too far beneath the surface, where the pressure raises the melting point but little above the prevailing normal temperature, the additional heat is sufficient to cause melting. This melting would begin interstitially, if the rock were basic or of intermediate composition. In acid materials the melting would affect the mass as a whole.[45]

[44] W. J. Mead, "The Geologic Rôle of Dilatancy," *Jour. Geol.*, Vol. 33, 1925, pp. 685-98.

[45] "Many granitic magmas may have their immediate origin in the remelting . . . of a granite derived in more remote times from basic material." N. L. Bowen, *The Evolution of the Igneous Rocks*, Princeton, 1928, p. 319.

Mead has pointed out that the zones of schist so commonly found marking planes of movement in massive igneous rocks may well represent zones of dilatation under stress which as such would attract available water and other fluids in spite of the enormous compressive stress under which they originated. He goes farther. He concludes "that great and comparatively rapid deformations of the earth's crust may extend far below the surface and well into the zone normally characterized by rock flowage. If this is at a depth where the rocks are at a temperature above their melting point but are kept solid by pressure, the result of fracture-dilatation would be immediate liquefaction of the rock in that zone to an extent measured by the increase in volume. This fluid rock migrating by way of the fracture zone to regions of lower pressure would remain fluid and contain sufficient excess heat to fuse a certain amount of rock in its path. The presence and movement of this fluid material would considerably upset the dynamic stability of the whole, and result in the development of magma and magmatic activities of greater or lesser extent, depending on the magnitude of the original deformation."[46]

The fractures produced because of the dilatant behavior of the rock mass, would primarily consist of innumerable small, intergranular fractures. The result of the process suggested by Mead would not be fundamentally different from the interstitial melting which the writer mentioned above.

Whether the liquefaction takes place in one or the other or in both ways simultaneously is of little consequence to the larger process involved. The liquid would be produced here and there throughout the crustal rock matter in small quantities. All the while, however, the same crustal column would be lengthened, drawn out downward. It seems again reasonable that this downward squeezing of the rock mass would tend to cause the liquids to coalesce and to work upward because of their smaller density. Slowly they would form larger reservoirs of fluid magma not necessarily at an absolutely higher level, but higher with reference to the crustal material within which it came into existence.

Not until it had reached considerable dimensions would such a magmatic reservoir become an instable element. If orogenic pressure continued indefinitely, it seems possible that the body of liquid

[46] W. J. Mead, *op. cit.*, p. 696.

might cause catastrophal movements if it started after the fashion of injective ("diapir") folds to break through the outer crust. Observation teaches us that as far back as the record is clear, granitic magmas had accumulated in sufficient size to rise effectively in the crust only by the time the orogenic stress was diminishing. As large or small plates and blocks of the overlying roof of the magma reservoir spalled off the lighter, mobile magma took their place. In most cases the magma seems to have had so little superheat that resorption has been negligible.

As it rose nearer the surface, it lost heat at a greater rate. The rate of rise seems to have been such that generally crystallization overtook the magma before it could pour out on the surface in lava floods such as the rhyolites of the Yellowstone plateau.

Taken as a whole, the creation of the magma and its movements have been an inseparable part of crustal tectonics at large. In this sense, Cloos and Stille have spoken of magmatic movements as simply a phase of crustal tectonics, that of its most mobile material.[47]

It seems that this picture of the mechanism of intrusions implies automatically the behavior of magmas which is expressed in laws 30 to 32. Note especially how it accounts for the eccentric position of post-folding intrusions. It seems obvious that in orogenic zones which are strongly asymmetrical, all deeper deformation of the crustal mobile zone must take place in the direction of major shear zones. This means that the crustal body undergoing deformation would extend in an inclined position downward into the crust in the direction from which the pressure acted. This would carry the zone in which magmas come into existence obliquely downward into the crust, exactly on that side which law 31 specifies. Since the ultimate rise of the magma to the surface is largely a following-up in a vertical direction of rock units spalling off, the intrusions would come to the surface in the characteristic eccentric fashion.[48] In the more symmetrical

[47] e.g., H. Stille, *Grundfragen der vergleichenden Tektonik*, Berlin, 1924, p. 256.

[48] In this discussion the phenomena of volcanism are being left out of consideration since purely accidental features determine largely whether magmatic materials shall reach the surface or not. Because of the accidental nature of many of the conditions which determine the extrusion of lavas, it is difficult to see the larger factors which determine their appearance. At this point, however, attention may be called to the well known habit of volcanoes to be located on the inside of an arcuate welt, for which the East Indian Archipelago offers especially striking examples.

welts of the heterogeneous belts, of which we shall have to speak later, they would rise nearer the center.

Structural relations of concordant acid intrusives. The preceding picture of the ultimate rise of acid intrusives is based on the "discordant" type, that is, bodies that cut across the preexisting rock structure. Evidence is accumulating rapidly, however, which shows that especially in pre-Cambrian terranes there are also concordant bodies of acid intrusives. Excellent examples of this type have been described recently by A. F. Buddington from the northeast side of the Adirondacks. There they constitute the typical form of acid intrusives. Two of these may serve as specific examples for this discussion. Figs. 78

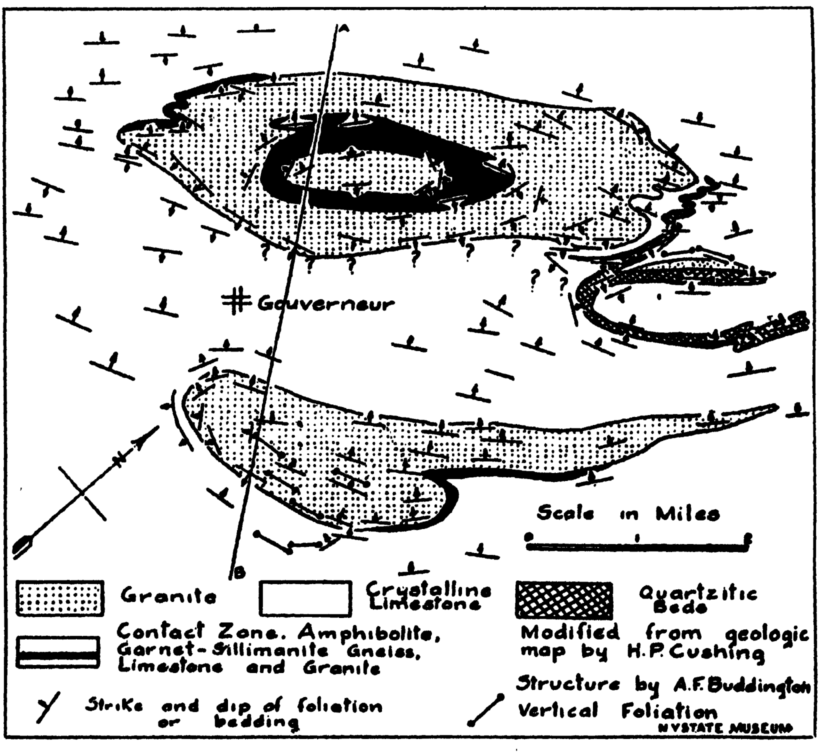


Fig. 78. Tectonic sketch map of the Gouverneur and Reservoir Hill phacoliths in the northwest Adirondacks, New York.

(A. F. Buddington, 1929)

and 79 show them in map and cross-section.[49] They lie north and east respectively of the town of Gouverneur,[50] about twenty miles

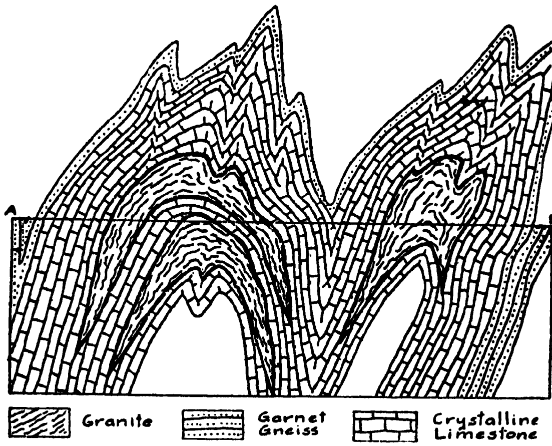


Fig. 79. Inferred structure-section across Gouverneur and Reservoir Hill phacoliths along line *A-B* of Fig. 78.
(A. F. Buddington, 1929)

southeast of the St. Lawrence River (Thousand Islands). They consist of gneissoid granite and are wholly enclosed in Archeozoic (Grenville) crystalline limestone.

Both map and cross-sections show that the foliation within the granite is domed and conforms remarkably to the dip and strike of the surrounding limestones, on the noses as well as on the limbs of the folds. The northern body actually consists of two sheets of granite separated by a layer of "interbanded Grenville metamorphics and intrusives" five hundred to seven hundred feet thick. Here, then, not only the top but also the base of one of the granite sheets is actually exposed.[51] This outer sheet of granite is between seven hundred and eight hundred feet thick on the southeast limb and somewhat thicker on the northwest limb. It is exposed over an area five and one-half

[49] Reproduced from A. F. Buddington, "Granite Phacoliths and Their Contact Zones in the Northwest Adirondacks," *New York State Mus. Bull. 281,* 1929, Figs. 34 (p. 55) and 35 (p. 56).

[50] Compare also geological map of Gouverneur Quadrangle (1 :62,500) by H. P. Cushing, in *New York State Mus. Bull. 259,* 1925.

[51] In one other case, that of the much larger Canton intrusive, the base is widely exposed. See Buddington, *op. cit.,* pp. 65-71.

miles long and one and one-half miles wide. Cushing's geological map shows the granite cutting across bands of impure siliceous limestone and schists on the southeast side of the mass. This relation Buddington could not verify because of lack of outcrops. He thinks that there may well be "some cross-cutting of the Grenville by the granite," but "not of a character or sufficient in amount to vitiate"[52] his interpretations of an essential conformity of intrusive and surrounding limestones.

The map creates altogether the impression that these bodies are sheets or sills of granite material folded with the sediments in which they lie. But here the other outstanding property of these granite bodies enters decisively. Thin sections cut from them fail to reveal signs of either protoclastic or cataclastic structure, that is, fracturing of crystals due to crushing either in a partly liquid, partly solid mixture, or after complete consolidation. Only one conclusion is possible: the granite melt must have been still essentially liquid at the time of the folding.

It is probable that the fluid pressure of these masses of granitic liquid in the crests of anticlines, advancing upward differentially with reference to the surrounding sedimentary rocks, was responsible for the cross-folding which is conspicuous here and there with trends running at right angles to the normal regional strike. There has been here, as elsewhere, a tendency to invoke secondary orogenic stresses (of unknown origin, of course) at right angles to the regional stress to account for this cross-folding. Buddington very properly remarks that "the magma itself acted as an agent in making these forces effective. The results are as though a minor tectonic force or component acted contemporaneously" at right angles to the normal regional stresses.

This picture fits essentially all concordant intrusives elsewhere. The question is: What relation do these concordant intrusives bear to the discordant type? It is generally assumed that they represent the acid magma forced upward into the sedimentary mantle from below while the folding was in progress. One great difficulty, however, presents itself. Taking our Adirondack examples, we find the thin sheets of granite folded essentially conformably with limestones under conditions of folding under which the limestone must have

[52] Buddington, *op. cit.*, p. 57.

yielded by flowage. Buddington speaks, for instance, of pegmatite veins that "have been broken into angular fragments and pulled apart by flowage of the inclosing limestone." At other points, pegmatite veins were wrinkled in the fashion so well known from all metamorphic regions, with the limestone flowing about them with perfect "plasticity." How shall we picture the mechanism by which thin sheets of granitic magma, a few hundred feet thick and tens of square miles in area, were introduced between the limestone layers? Have we any reason to assume that when one more mobile medium is forced upward into another less mobile medium, both capable of flowage under the existing confining pressures, the one will interleave delicately with the other rather than push it aside in irregular masses? The writer suspects that the answer should be "no."

Only one alternative view seems possible. The granite must have formed sills and sheets[53] previous to the folding of the bedded rocks or during the initial stages of folding and the orogenic pressure must have acted soon enough after the intrusion to find the igneous melt still essentially liquid.

We know that the larger orogenic phases of mobile belts consist of several epochs of compression separated by shorter epochs of rest or even of tension (pp. 139 to 141). If granitic magmas became available, in quantity, through the orogenic stresses of the early epochs of compression, they might well find their way in quantity into the mantle of gently folded sediments. If the interval to the next epoch of compression were sufficiently short, the magma would be still liquid. It would, with its greater mobility, be forced into the anticlines and synclines or into such positions as its hydrodynamic behavior would dictate.[54]

It seems obvious that after closed folding and schistosity have once been developed, later intrusives cannot enter any more into such simple relations to the structure of the folded sediments. The earliest intrusives, then, in an orogenic zone would be conformable while all later ones would be more or less disconformable. This seems to have

[53] See A. Harker, *The Natural History of Igneous Rocks,* New York, 1909, p. 79.

[54] The Caledonian intrusive bodies in the Sulitelma region of northern Norway which Th. Vogt has recently interpreted as "phacoliths" lie neither in synclines nor anticlines. Vogt believes their position is due to the circumstance that the magma found it easier to compress the strata laterally than to lift it vertically. Th. Vogt, "Sulitelma feltets geologi og petrografi," *Norges Geologiske Undersökelse, No. 121,* Oslo, 1927. Quoted from the review in *N. Jahrb. f. Min.,* etc., 1929, II, pp. 349-58.

been true generally of Archeozoic orogenies, but not of later ones. This is a very curious fact. It deserves a fuller statement.

Age of concordant acid intrusives.

Law 35. Large concordant acid intrusives in folded sediments are widespread only in early pre-Cambrian terranes.

In North America, the beautiful maps which accompany Adams and Barlow's Memoir[55] on the Haliburton and Bancroft areas of southern Ontario have furnished the type material for discussions on concordant intrusives. A fine case of a gneissic granite sheet occupying a synclinal position in Grenville metamorphics at the southern border of the pre-Cambrian region of Ontario was recently published by Wilson.[56] The gneissoid granites of the Adirondack region are in every way a direct continuation of the same pre-Cambrian orogenic unit.

The story of the earlier gneissoid granites of the Laurentian shield is duplicated by that of the analogous granites of the Baltic shield. There the older gneissoid granites bear to the leptite[57] formation the same relation which the Laurentian gneiss bears to the Grenville and Keewatin rocks. Högbom's sketch map of the Archean of a part of Upland[58] is the exact counterpart to the structure shown on Adams and Barlow's map. In both regions, schistosity and stratification are parallel in the metamorphosed sediments,[59] a condition which in itself offers a remarkable problem. Both schistosity and stratification follow the contours of the granitic intrusives and the schistosity within these so closely that in both regions the gneissoid granites were interpreted as lenticular intercalations in the crystalline sediments. In the third edition of Dana's *Manual of Geology* (1880) we read (p. 152): "Although the Archean rocks are mostly crystalline, they

[55] F. D. Adams and A. E. Barlow, "Geology of the Haliburton and Bancroft areas, Province of Ontario," *Canada Geol. Survey, Memoir 6,* 1910. See also F. D. Adams, "The Origin of the Deep-Seated Metamorphism of the Pre-Cambrian Crystalline Schists," *Congrès géol. internat., XI, 1910, Compt. Rend.,* Vol. I, 1912, pp. 563-72.

[56] M. E. Wilson, "The Grenville Pre-Cambrian Subprovince," *Jour. Geol.,* Vol. 33, 1925, p. 398, Fig. 2.

[57] Fine-grained schists rich in feldspar, probably metamorphosed volcanic tuffs and tuffaceous sediments.

[58] A. G. Högbom, "Pre-Cambrian Geology of Sweden," *Bull. Geol. Instit., Univ. of Upsala,* Vol. 10, 1910-11, Fig. 11.

[59] Per Geijer, "On the Intrusion Mechanism of the Archean Granites of Central Sweden," *Bull. Geol. Instit., Univ. of Upsala,* Vol. 15, 1916, pp. 50-1.

follow one another in various alternations, like the sedimentary beds of later date. In the sections which have been given, there are alternations of granite, gneiss, schists, limestone, etc.; and the dip and strike may be studied in the same manner as in the case of any tilted sandstones or shales." In the same year Törnebohm in the introductory text to his geological map of central Sweden[60] interpreted these gneissoid intercalated granites as surface flows. There never has been any danger of such an interpretation in the cases of such later intrusives in which a certain correspondence exists between the strike of the surrounding sedimentary rocks and the major boundaries of the intrusive bodies.

Recently, Erich Kaiser has given a detailed description of the Archean of the Namib desert of southwest Africa,[61] where the exposures on the barren rock surfaces rival those of the glacially denuded regions. Exactly as in Canada and Fennoscandia, the oldest granitic intrusives are typically concordant gneissoid granites. They range from the thin plates of lit-par-lit injections ("arterites") to thicker sill-like bands and large lenticular bodies, all intruded into the sedimentary gneisses and schists of the region. The parallelism between granite body and the metamorphosed sediments extends to the schistosity of the granite and the alignment of fragments of wall rock. The younger pre-Cambrian granites of this region, as elsewhere, are discordant, in strong contrast to the oldest conformable intrusions.

These three examples may suffice to illustrate the law. The regular occurrence of conformable acid intrusives in the Archean stands curiously in contrast to most intrusions of later date. It is as if in later times granitic magmas had not been able to reach the sedimentary mantle in quantity during the earlier compressive epochs of an orogenic phase or perhaps did not form at all.

Perhaps the crust was in a different physical condition during earliest recorded geological time. There are other phenomena that are widespread only in Archean terranes, especially those which indicate a transition from the solid to the liquid state of crystalline rocks,

[60] A. E. Törnebohm, *Geol. Öfversiktskarta Öfver Mell Sveriges Bergslag*, Stockholm, 1880, p. 48.

[61] Erich Kaiser, *Die Diamantenwüste Südwestafrikas*, Berlin, 1926, Vol. I, pp. 58-67.

a partial liquefaction of solid parts of the crust, the "anataxis" of Sederholm.[62]

It is customary to speak of the structure of the Archean rocks as being the product of processes that have been operative "at great depths." But there seems little reason for this assertion. The Epi-Archean peneplain truncates these structures. Why should the structures revealed by Epi-Archean base-levelling differ from those exposed by, say, Epi-Carboniferous erosion to base-level? We are deceived by the subconscious thought of the great sediments that have accumulated on top of the Archeozoic rocks in some parts of the world. If we are to believe that the Archeozoic structures originated at greater depth than those revealed of later date, we must also assume that greater amounts of rock were removed by erosion during Epi-Archean peneplanation than at any time since. The writer knows of no observation which would support this assumption.

If the Archean structures were not formed at greater depth, they must owe their peculiar character to a condition of the crust different from that which prevailed during later times. This condition must have been such that granitic magmas formed more readily than later.[63] If they formed more readily, they may also have formed more frequently. We shall show later that there is independent reason for such an assumption.

Résumé. We may sum up the results of the preceding discussion as follows:

Opinion 25. The granitic magmas of the orogenic zones have come into existence as by-products of orogenic deformation. They rose to the surface differentially, as the most mobile of the materials undergoing essentially "plastic" deformation.

Opinion 26. Most later intrusives reached the uppermost portion of the crust only as the orogenic pressure was dying down, reaching their final positions by changing places with solid crustal materials through the action of gravity rather than of the orogenic pressure (discordant type). Only in early pre-Cambrian time did granitic mag-

[62] J. J. Sederholm, "Die regionale Umschmelzung (Anataxis), erläutert an typischen Beispielen," *Congrès géol. internat., XI, 1910, Compt. Rend.,* Vol. I, 1912, pp. 573-95.

[63] Daly, e.g., speaks of the earth's crust as "especially thin and weak in that early epoch." R. A. Daly, *Igneous Rocks and Their Origin,* New York, 1914, p. 205.

mas invade the mantle of sediments early in the orogenic phase (concordant type).

Terms. In the preceding discussion, the writer has purposely avoided the terms "batholith" and "phacolith." To each of these terms some specific connotation of hypothetical interpretation in addition to an objective definition of form is still apt to be clinging. Thus Harker ascribed the bodies of what he called "phacolites" to "a concurrent influx of molten magma" which will find its way along the crests and troughs of the folds where there is "a relief of pressure and a certain tendency to opening of the bedding surfaces."[64] It seems safe to say that this mechanism cannot have been at work at least in the final fashioning of Buddington's phacoliths in the Grenville limestones.

Suess conceived his "batholiths" originally as formed in cavities due to the lifting of crustal slabs. "The magma simply filled the space as far as it extended, and consolidated in it, forming a cake of rock or true batholite."[65] Later observations convinced him "of the fact that the contours of these intrusive masses cut through both the strike and the folds of the mountains in the most uncompromising fashion, much as a white-hot soldering-iron thrust through a plank cuts across the grain."

He redefined the term, therefore, to mean "intrusive masses, which are continued down into the eternal depths . . . having reached their present positions . . . by melting and absorbing the adjacent rock."[66] Again the hypothetical parts of this definition are rejected today by most geologists.

In the coining of scientific terms, the coupling of hypothetical concepts with terms of objective reality has always led to needless multiplications of terms and, much worse, to confusion of issues. Even in such a term as "peneplain" the hypothetical implication in the definition that it is the result of base-levelling *after* uplift has been a serious obstacle to physiographic analysis.

The writer would urge, therefore, that the actual trend of usage be developed into a firm policy and that geological terms which involve

[64] A. Harker, *The Natural History of Igneous Rocks,* New York, 1909, p. 77.

[65] E. Suess, *The Face of the Earth* (English trans. by Sollas and Sollas), Vol. I, p. 168.

[66] *op. cit.*, Vol. IV, pp. 551-2.

in their definitions facts of objective nature be stripped of all subjective implications. In that sense, the term "batholith" should be used for fairly large discordant intrusive bodies, whatever may be their hypothetical form and origin. Concordant intrusives in folded rocks should be called "phacoliths" and in otherwise undisturbed rocks, "laccoliths" (and "sills"). This is virtually the sense in which "phacolith" has been employed, e.g., by Buddington, Kaiser, Vogt, in the papers quoted above. It is also virtually the sense in which "batholith" is used in current literature.

4. The Melting Point of Acid Crystalline Rocks

The dilemma of the field geologist. The readiness with which granitic magmas have come into existence wherever orogenic pressures were active should lead one to suppose that for materials of this composition the transition from the solid to the liquid state is easily accomplished, at least as readily if not more so than in the case of more basic rocks. The relative behavior of basic and acid rocks under the conditions which have been explained by remelting ("anataxis") points in the same direction.[67] Whatever one may think about anataxis in its application to any specific case or as a concept (as which it goes back to Hutton), one curious fact remains. Softening and remelting was typically inferred for (metamorphosed) sediments and acid rocks rather than for basic rocks such as metabasalts, amphibolites, etc., which are so widely distributed in pre-Cambrian strata. Obviously the field experience of the geologist was in conflict with the generally accepted "fact," that basic materials have a decidedly lower melting point than acid rocks.

This conflict should have been disconcerting to those who based comprehensive theories of earth-deformation on the difference in the melting points of gabbroid and granitoid materials. Airy's "roots of

[67] For opinions concerning Sederholm's interpretation see, for instance, the discussions concerning pre-Cambrian geology during the XI International Geol. Congress at Stockholm (*Congr. géol. intern., XI, 1910, Compt. Rend.*, Vol. I, pp. 734-40 and pp. 1324-9). Also a number of the papers read at that congress, esp. Sederholm's papers on "Die regionale Umschmelzung (Anataxis), erläutert an typischen Beispielen," *op. cit.*, pp. 573-86, and "The Subdivision of the Pre-Cambrian of Fennoscandia," *op. cit.*, esp. pp. 686-93; Königsberger's paper on "Die kristallinen Schiefer der zentralschweizerischen Massive," *op. cit.*, esp. pp. 660-5. Also J. J. Sederholm "Über die Entstehung der migmatischen Gesteine," *Geol. Rundschau*, Vol. 4, 1913, pp. 174-85.

mountains" are possible only if the acid materials of the crust possess greater strength than the basic substratum. There should not be any melting of the acid materials as they are pressed down into the basalt layer beneath them. If there is any melting, it must be the basalt that melts, not the base of the acid crust. Yet in the course of every important orogenic phase granitic magmas sprang into existence in quantity in the higher parts of the crust. This inconsistency should have caused serious concern. Joly's impressive theory is built on the conviction that granitic rocks may remain immersed in molten basaltic rock, in the case of the Tibetan Plateau, to a depth of thirty kilometers (twenty miles). In speaking of this colossal compensating mass, Joly says: "Even if our coefficient is excessive and we accept one based on a lower estimate of continental density, it can be shown that the temperature within its great compensation due to its own radioactivity must locally attain to 1,500° C., which (under surface conditions) would suffice to melt or soften the feldspars of the granites, leaving, however, the ground mass of the rock (quartz) rigid."[68] A footnote states explicitly that the melting point of quartz approximates to 1,700° C.

In one form or another the thought of the high melting points of the constituents of acid igneous rocks, especially of quartz, has influenced the conviction of most geologists that they must melt at higher temperatures than basic rocks. But in view of the complicated relations that enter into the melting point of mixtures, few would have thought of the melting of granite in such simple terms as Joly uses in the above quotation.

The dilemma of the petrologist. Petrologists faced a dilemma similar to that of the field geologists ever since Rosenbusch enounced, in 1882, the empirical law of the order of crystallization of minerals in igneous rocks. This states that "the separation of crystals in a silicate magma follows an order of decreasing basicity, so that at every stage the residual magma is more acid than the aggregate of the compounds already crystallized out,"[69] with free silica as the last to

[68] J. Joly, *The Surface-History of the Earth,* Oxford, 1925, p. 52. In the original publication of his theory, Joly ascribed the origin of batholiths to "local liquefaction." J. Joly, "Movements of the Earth's Surface Crust," II, *Philos. Mag.,* Vol. 46, 1923, pp. 170-5.

[69] Quoted from A. Harker, *The Natural History of Igneous Rocks,* New York, 1909, p. 181.

crystallize. Such a behavior seemed "to be in direct conflict with the laws of solutions." It was thought necessary to invoke the aid of volatile constituents to explain the discrepancy. It remained strange, however, that so universal and uniform a behavior should result from factors which by their very nature should be expected to be highly variable in distribution both in vertical and horizontal directions.

The obvious conclusion should have been rather that it is normal for the most acid fraction of the crystallizing magma to remain liquid at the lowest temperatures. The intensive study of carefully controlled binary and ternary systems of silicate mixtures, chiefly at the Geophysical Laboratory of the Carnegie Institution, has demonstrated that this is the case. The physicochemical relations involved were worked out especially by Bowen.[70] In view of this result the petrographer should have expected to find the melting point of acid silicate rocks lower than that of the basic. Like the field geologist, he found the results of his studies in contradiction to what was accepted doctrine concerning the melting point of silicate rocks.

The older melting point determinations. In a matter of such fundamental importance as that of the relative melting points of acid and basic silicate rocks, one should expect explicit statements in the literature on earth deformation concerning sources of information on which the accepted view rests. Quite to the contrary, however, such treatises generally offer little more than vague statements. Iddings, for instance, merely states categorically that "the melting point of the rhyolitic lava is much higher than that of basalt, probably 50 per cent higher."[71] Joly merely affirms that under similar conditions of pressure (at the base of the acid crust) the melting points of the "average continental rock" range from 1,400° to 1,700° C. while that of basalt lies below 1,200° C.[72] Wegener uses the results of Doelter's experiments in the form of the generalized statement that "the melting point of sial rocks is in general 200° to 300° higher than that of the sima, so that magmatic sima and solid sial could exist side by

[70] N. L. Bowen, "The Reaction Principle in Petrogenesis," *Jour. Geol.*, Vol. 30, 1922, pp. 177-98; *The Evolution of the Igneous Rocks*, Princeton, 1928.

[71] J. P. Iddings, *The Problem of Volcanism*, New Haven, 1914, p. 17.

[72] J. Joly, "Movements of the Earth's Surface," I, *Philos. Mag.*, Vol. 45, 1923, p. 1170.

side at the same temperature."[73] Daly is more explicit in his *Igneous Rocks and Their Origin*, quoting experiments by Doelter and by Fouqué and Michel Lévy[74] which indicated higher melting points for acid than for basic rocks. But even in this excellent work one misses critical evaluation of the methods used in the light of the difficulties inherent in the determination of melting points of crystalline mixtures which differ greatly in the rate at which interstitial melting progresses and in the viscosity of the resulting melt. Somehow the refractory nature of pure silica gave such an air of plausibility to the results of the various, rather casual, experiments performed since Hall's pioneer work that scepticism seemed out of place. Since the writer shared fully in this uncritical attitude toward a group of facts on which enormous superstructures of theory had to rest, he is free to hold it up as a warning example.

Greig and Shepherd's results. Recent work by Greig, Shepherd, and Merwin of the geophysical laboratory of the Carnegie Institution of Washington has demonstrated beyond doubt that the traditional view is wrong. Greig, Shepherd, and Merwin gave a brief account of their experimental work at the meeting of the Geological Society of America in New York in 1928.[75] Since no fuller account has appeared in print, the following comment by Dr. Greig is quoted from a letter.[76]

"As with most experimental work, it is not possible to make a brief summary statement of the results that will by itself be rigidly true. It would be necessary to describe in some detail the conditions under which our experiments were conducted. However, while it cannot be said that there was no water vapor present, the amount of it was very small indeed. We found that the temperatures of complete melt-

[73] Quoting C. Doelter, "Petrogenesis," in *Die Wissenschaft,* Vol. 13, 1906. (A. Wegener, *The Origin of Continents and Oceans,* English trans., 1924, pp. 136-7.)

[74] The experiments by Barus and Iddings which the writer had heard quoted repeatedly and which unquestionably did much to establish the current view of the higher melting point of acid rocks in the United States are not quoted in the *Bibliography of North American Geological Literature* under Barus' name. Nor did the writer find the paper quoted in the literature consulted. It appeared in the *Am. Jour. Sci.,* Vol. 44, 1892, pp. 242-9, esp. pp. 245-6. (Carl Barus and J. P. Iddings, "Note on the Change of Electric Conductivity Observed in Rock Magmas of Different Composition on Passing from Liquid to Solid").

[75] J. W. Greig, E. S. Shepherd, and H. E. Merwin, "Melting Granite and Basalt in the Laboratory" (abstr.), *Bull. Geol. Soc. America,* Vol. 40, 1929, pp. 94-5.

[76] The writer wishes to thank Dr. Greig again for permission to publish this part of his letter.

ing for rocks of granitic compositions are lower than for basaltic rocks, and that in general among the granitic rocks this temperature decreases with increasing silica content. Further, we found that the melting interval was much greater in the case of the two granites we used (most of our work was on lavas) than in the case of the basalts so that if we were considering the temperatures at which flow could take place we would find it much lower in the granites than in the basalts. The two granites used would certainly flow below 800° C. if given time enough, for we formed about 50 per cent glass at that temperature and of course the fluxing had not reached completion. We formed only a small amount of liquid in the basalts of 1,100° C., although those that we worked on were completely liquid at about 1,185° C."

The worst is that according to Bowen[77] it was a "foregone conclusion to anyone familiar with the thermal properties of the universal constituents of the two rocks," basalt and granite, that even in the complete absence of water, the latter should melt at lower temperatures than the former. We should have found this out twenty years ago.

This result destroys the physical basis for Airy's concept of "roots of mountains" and with it all theories based upon it. It renders unnecessary pages of argument in earlier parts of this book. The writer let them stand in full, however, as they serve in their independent way to strengthen the reasoning from known facts, which is the very essence of this book.

[77] N. L. Bowen, *The Evolution of Igneous Rocks,* Princeton, 1928, footnote on p. 298.

CHAPTER X

HETEROGENEOUS MOBILE BELTS AND FAULTED BELTS OF LOW MOBILITY

Belief in the simplicity of nature is not logic but faith pure and simple.
J. W. Mellor, in *Modern Inorganic Chemistry,* 1920.

I. HETEROGENEOUS MOBILE BELTS

1. The Coast Ranges of California

At the beginning of the preceding chapter the concept of "heterogeneous mobile belts" was introduced in contrast to the type which generally figures in discussions on orogeny which was called "homogeneous." The latter, throughout their geosynclinal and orogenic phases, have behaved essentially as single units. The deformation of the heterogeneous belts offers a very different picture. We find the best American example in the Coast Ranges of California.

The peculiar nature of the heterogeneous geosynclinal belts is expressed in their structure by two properties exhibited in the Coast Ranges:

1. The sedimentary formations thicken and thin suddenly, more so at right angles to the structural axes than parallel with them.
2. The lines along which the abrupt changes of thickness are observed coincide generally with recognized fault lines or zones of faulting.

The first of these may be illustrated by the conditions in the San Francisco[1] region.

The Cretaceous formations, which total over 7,000 feet northeast of San Francisco Bay in the area northeast of the Berkeley Hills, are missing completely beneath the Eocene beds of San Pedro Point, south of San Francisco. The Eocene in turn, which reaches a thickness of over 4,000 feet nine to ten miles northeast of the Berkeley Hills, is completely absent on the northeast flank of the Berkeley Hills. Oligocene sediments of San Lorenzo age are not found within

[1] A. C. Lawson, *San Francisco Folio (Folio No. 193), U.S. Geol. Survey,* Washington, 1915.

the area of the San Francisco Folio. But in the region immediately adjoining on the south, that of the Santa Cruz Folio,[2] they are over 2,500 feet thick. The Miocene formations, which total over 7,500 feet in the thick folded series of sediments northeast of the Berkeley Hills, pinch out completely where the Pliocene Merced formation overlaps on the Franciscan rocks north and south of the Golden Gate.

The second property seems to have been first fully appreciated and expressed in graphic form by Lawson[3] in his description of the San Francisco Folio. He recognized especially that some of the faults which bound the areas of different sedimentary records date back to pre-Tertiary times, while others came into existence during various stages of the Tertiary.[4] Detailed studies in many regions have proven this to be typical of the California Coast Ranges in general.

The fact that different units of the Coast Ranges hold widely different stratigraphic records and that the transition from one unit to the next is generally abrupt, having the character of a flexure or a fault zone, was more and more recognized as detailed knowledge grew during the last two decades. F. M. Anderson and Bruce Martin (1914), A. C. Lawson (1915), W. A. English (1916), J. O. Norland (1917), Bailey Willis (1920), R. T. Hill (1920), and others set forth the critical facts and their bearing on the diastrophic history of the Coast Ranges.[5] The most comprehensive picture of Coast Range structure, limited to the Coast Ranges of middle California, has been given by Bruce L. Clark. The major fault zones are shown on a tectonic sketch map which is here reproduced in Fig. 80.[6] The structural and stratigraphic relations are illustrated in Clark's paper by a detailed discussion of six cross-sections drawn across the Coast Ranges at different points between San Francisco Bay and Santa Barbara. The

[2] J. C. Branner, J. F. Newson, and Ralph Arnold, *Santa Cruz Folio, Geologic Atlas of the United States*, No. 163, 1909.

[3] See the tectonic sketch map, Fig. 3, in the text of the *San Francisco Folio*, 1915. In the earlier folios located in the Coast Ranges, no faults appear on the geologic map although they are discussed in the text and are assigned a rather important rôle in dividing the areas into a number of distinct orographic and structural units during Neocene time.

[4] See also Bruce L. Clark, "Age of Primary Faulting in the Coast Ranges of California," *Jour. Geol.*, Vol. 40, 1932, pp. 385-401.

[5] For references see chapter "Historical Review," pp. 810-15 in Bruce L. Clark, "Tektonics of the Coast Ranges of Middle California," *Bull. Geol. Soc. America*, Vol. 41, 1920, pp. 747-828.

[6] Reproduced from Pl. xvi, opp. p. 770, of B. L. Clark, *op. cit.*, 1930.

locations of these six cross-sections are shown on Fig. 80. The first two of these sections are here reproduced in Figs. 81 and 82.[7]

Turning first to the map, note the wavy fault line which borders the cross-section *A-A* on the northeast. It represents the trace of the Mt. Diablo thrust sheet, as mapped by Clark.[8] South of the edge of this thrust sheet and nearly parallel with its margin, runs the Riggs Canyon fault. It bounds the "Altamont block" on the southwest, the easternmost block of both cross-sections (marked "G" in section *A-A*; J in section *B-B*). The sections show that it consists essentially of Cretaceous formations. In the north, beneath the thrust mass of Mt. Diablo, the Cretaceous beds form an asymmetrical anticline (section *A-A*). Southeastward this fold flattens and the Cretaceous rocks are overlaid by almost undisturbed Upper Miocene (Briones sandstone). Just across the Riggs Canyon fault, however, in the San Ramon synclinorium (block *F* on section *A-A*, block *I* on section *B-B*), there lie between the Upper Miocene and the Cretaceous more than two thousand feet of Eocene and several hundred feet of Oligocene and Lower Miocene beds. But in the narrow block which lies between the Sunol fault and the Wildcat Canyon fault, the Wildcat Canyon block (block *D* of section *A-A*), the Upper Miocene Briones sandstone again rests directly on the Cretaceous. The narrow block of the San Ramon synclinorium obviously received sediments during most of the interval between the Cretaceous and the Upper Miocene, while the other two blocks received none or suffered erosion. The change in the stratigraphic sequence coincides closely with the position of the fault lines.

Now turn to the southwestern end of section *B-B*, from Pigeon Point on the Pacific Coast to Palo Alto. This section is the same as the section *C-C* on the structure section sheet of Santa Cruz Folio.[9] In the section here reproduced, Clark distinguishes three blocks. The first (marked *A*) lies between the ocean and the San Gregorio fault.

[7] Reproduced from sections *A-A* and *B-B*, Pl. XVII, opp. p. 774 in B. L. Clark, *op. cit.* The sections were redrawn and labelled in a way suitable for use in this discussion.

[8] B. L. Clark, "Thrust-Faulting in the Region of Mount Diablo," *Min. and Oil Bull.*, Vol. 10, 1924, pp. 1133, 1181, 1200; "Thrust-Faulting in the Mount Diablo Region of Middle California" (abstract), *Bull. Geol. Soc. America*, Vol. 36, 1925, p. 152. (The same abstract also in *Pan-Am. Geologist*, Vol. 43, 1925, p. 150.)

[9] J. C. Branner, J. F. Newsom, and Ralph Arnold, *U.S. Geol. Survey, Folio 163*, 1909.

The second (marked *B*), the Santa Cruz synclinorium, is bounded by the San Gregorio fault on the west and the San Andreas fault on

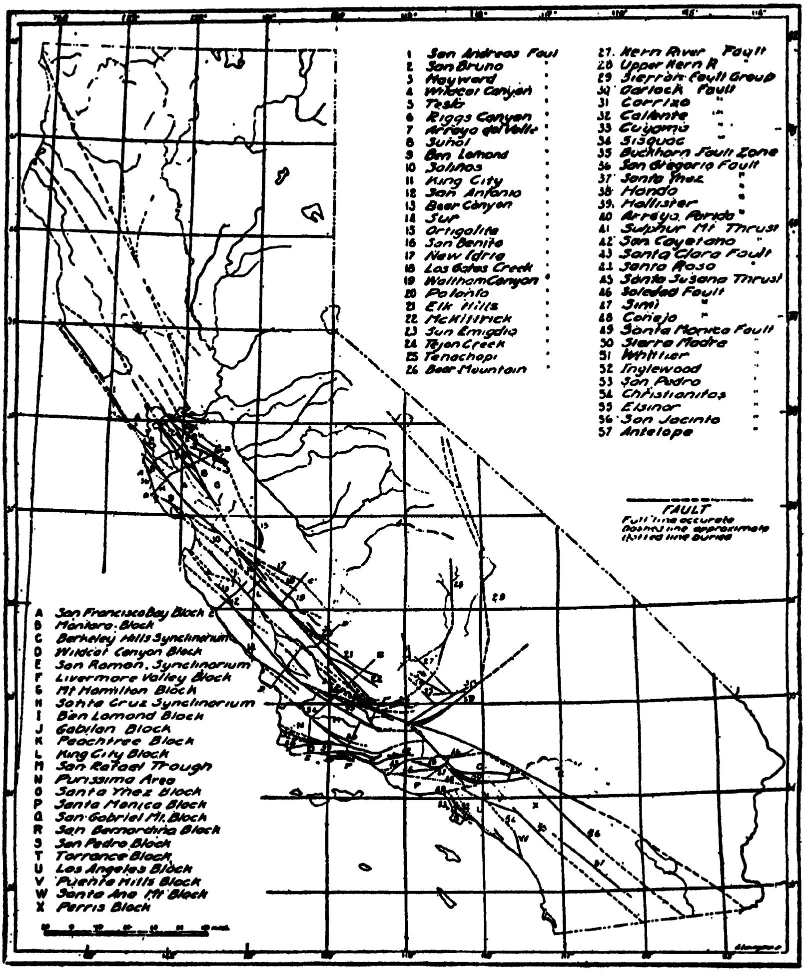


Fig. 80. Tectonic map showing the principal known fault zones in the Coast Ranges of California.

The figures refer to the list of names applied to the faults in the original publication. The cross-lines labelled at both ends by letters, such as *A-A'*, represent the locations of cross-sections given in the original publications. Sections *A-A'* and *B-B'* are here reproduced in Figs. 81 and 82.

(B. L. Clark, 1930)

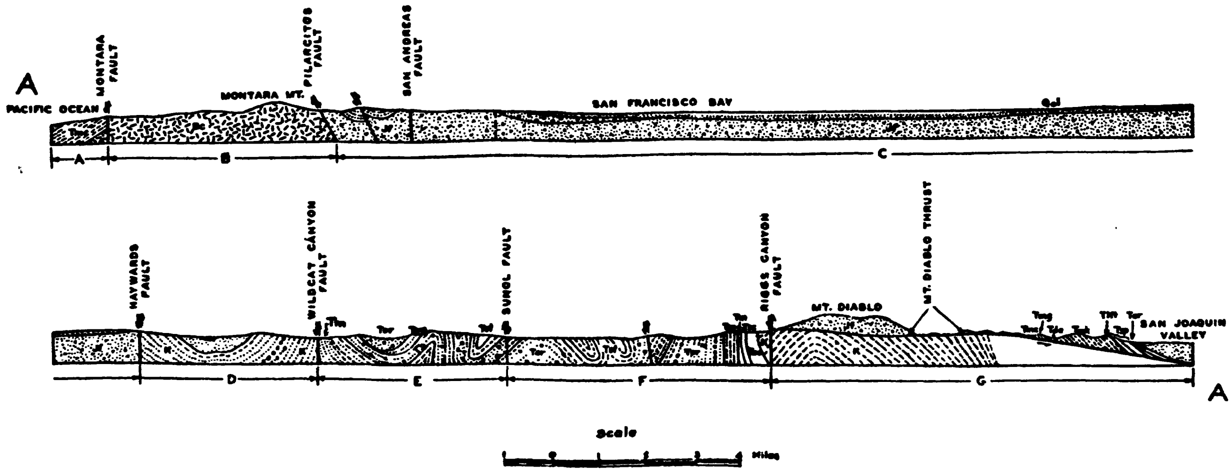


Fig. 81. Structure-section along the line *A-A'* of Fig. 80.

Symbols:

Recent: *Qal* = Alluvium
Pleistocene: *Sag* = San Antonio gravels
Pliocene: *Tl* = Livermore
Tsc = Santa Clara
Tst = Siesta
Tpa = Purissima
Tor = Orinda
Tme = Merced

Miocene: *Tsm* = Santa Margarita
Tsp = San Pablo
Tb = Briones
Tm = Monterey
Tv = Vagueros
Oligocene: *Tsz* = San Lorenzo
Tkt = Kirker Tuff
Tmk = Markeley Tuff
Tbo = Butano

Eocene: *Teo* = Eocene undifferentiated
Tde = Domengine
Tmg = Meganos
Cretaceous: *K*
Jurassic: *Jf* = Franciscan
Pre-Jurassic: *Bc* = Basement complex

(B. L. Clark, 1930)

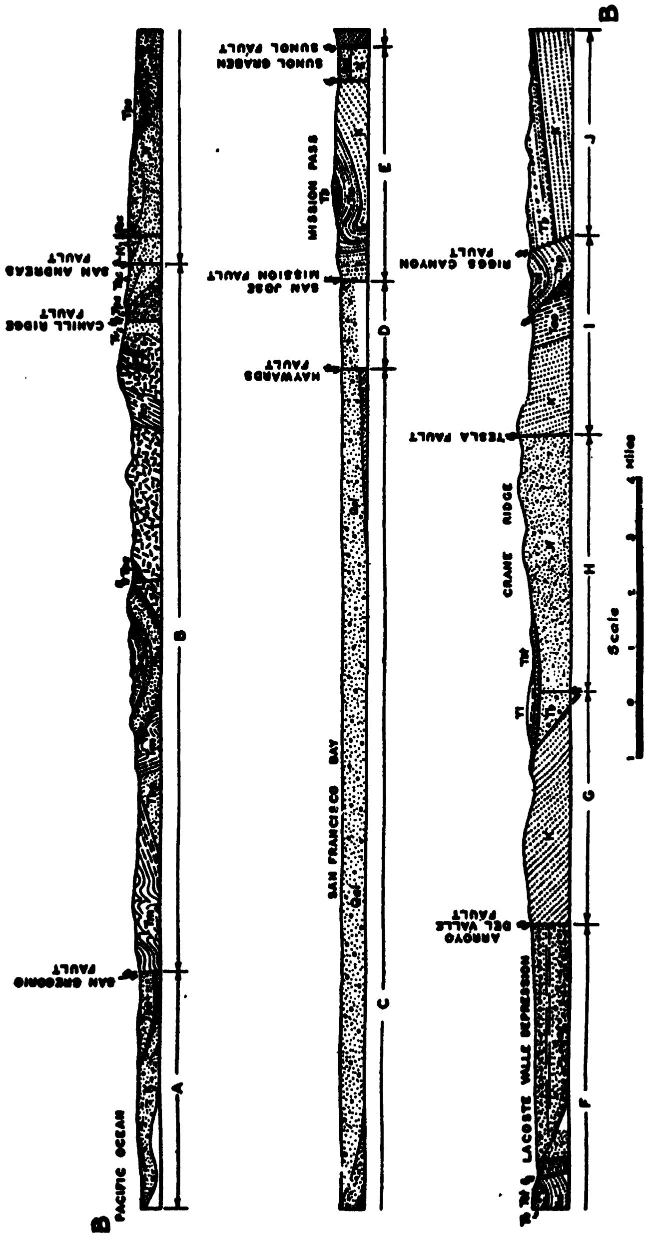


Fig. 82. Structure-section along line *B-B'* of Fig. 80.
Symbols the same as for Fig. 81.
(B. L. Clark, 1930)

the east. Between the latter and San Francisco Bay lies the San Francisco block. The blocks on both sides of the synclinorium carry Cretaceous sediments in good development. In the synclinorium itself, this section does not show any Cretaceous. A glance at the geological map of Santa Cruz Folio, however, shows that a few miles southeast of this section the pre-Franciscan quartz diorite emerges with the Tertiary resting directly on it! In other words, the block which later received some eighteen thousand feet of Tertiary strata either never had Cretaceous sediments deposited on it or had stood high enough at least before Oligocene time to have had eroded away whatever had been deposited on it. Then, while the great thickness of Tertiary beds was laid down on it, that is, while it sank, the blocks on both sides stood high enough not to receive any Oligocene or Miocene sediments. The section shows the marine Pliocene Purissima formation resting unconformably on the Cretaceous on both sides of the synclinorium,[10] while in the synclinorium itself there lies an enormous thickness of Oligocene and Miocene sediments beneath the Purissima formation. Note especially also that the lava flows and intrusive masses of diabase and basalt (of Miocene age) are largely limited to the synclinorium.[11]

Another abrupt change in the stratigraphic sequence along a fault zone is not at first obvious from the way the section *B-B* is drawn. West of the Sunol fault, Miocene beds rest on a thick Cretaceous series. Immediately east of the fault, the Miocene beds in "a somewhat different phase,"[12] rest directly on the Franciscan, on block *F* of section *B-B*. In the next block, *G*, east of the Arroyo del Valle fault, again several thousand feet of Cretaceous sediments appear. Thick Cretaceous sediments, then, are present both west and east of

[10] A small isolated patch of Lower Miocene is exposed southeast of Stanford University. See *Santa Cruz Folio.*

[11] The small flow of basalt which outcrops near Stanford University is shown in this section on the west flank of the anticline just west of the alluvium of San Francisco Bay.

[12] F. P. Vickery, "The Structural Dynamics of the Livermore Region," *Jour. Geol.,* Vol. 33, 1925, p. 611. (Vickery concludes that "structure, stratigraphy, and physiography show that blocks on opposite sides of the Sunol fault have had different histories.")

block *F*, but are absent from block *F* itself. "On the assumption of the former widespread deposition of Cretaceous in this general region, the presence of Cretaceous deposits on block *G* and their absence on block *F* can only be interpreted as the result of the uplift of the western block and the stripping of the Cretaceous before the deposition of the Lower and Upper Miocene sediments. Thus, the later movements on the Arroyo del Valle fault, which separates the two blocks, were reverse to the earlier. Reversal of movements on the major faults has been a common phenomenon throughout the Coast Ranges."[13]

Similar conditions prevail throughout the Coast Ranges, more particularly between San Francisco and Los Angeles, the part which is best known at the present. In the central portion of this region, for instance, northeast of King City, the Waltham Canyon fault forms an important boundary between two blocks of widely different history. On its east side, between the fault and San Joaquin Valley, a folded series of Cretaceous, Eocene, Oligocene, and Miocene strata nearly forty thousand feet thick rest on a Franciscan (Jurassic) basement. West of it, however, only a few hundred feet of later Tertiary (Miocene and Pliocene) lie directly on the Franciscan.

Structural history. These examples could easily be multiplied. Tracing these abrupt stratigraphic changes and the fault lines associated with them through the Coast Ranges, chiefly along the portion lying west of the San Joaquin Valley,[14] Clark arrived at the following picture of the structure and history of the Coast Ranges:[15]

1. Major zones of faulting and abrupt flexing divide the Coast Ranges into blocks. The individual blocks behaved differently in the course of orogenic history. Some were dominantly positive for long times, others dominantly negative. Sudden changes from depression to elevation and vice versa occurred frequently.

2. For any given time, the location and thickness of sediments formed was prescribed by the distribution of high and low blocks.

[13] B. L. Clark, *op. cit.*, pp. 779-80.

[14] *idem*, "Tectonics of the Valle Grande of California," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 13, 1929, pp. 199-238.

[15] This statement is based on Dr. Clark's papers and on personal discussions with Dr. Clark in the field.

Much of the sediment was derived from the high blocks. The thickness to which sediment accumulated at any point was largely determined by the rate and total amount of sinking of the depressed blocks.

3. At least since the end of Cretaceous time, folding has never affected the Coast Range belt uniformly. It was confined largely to the thick sediments of depressed blocks. Its effects were highly localized, the energy diminishing away from the faults and from the edges of elevated blocks.

4. Some of the important fault zones—and with them this type of orogeny—date back to pre-Tertiary and even pre-Cretaceous time.[16]

Turning once more to Fig. 80,[17] we shall now ask the important question how this peculiar type of "mobile belt" may be explained, especially in the light of the views concerning orogenesis developed in the previous pages.

2. The Mechanics of Coast Range Structure

Reid on the San Andreas fault. In his classic analysis of the mechanics of the earthquake of April 18, 1906, Reid came to the conclusion that the San Andreas fault is a shearing fracture produced by differential deep-seated flow in the direction of the fault plane, of isostatic origin, dragging the inert crust with it. The two concepts contained in this verdict still dominate thought concerning the San Andreas and the other dominant fault zones of the California Coast Ranges: (1) Their origin through shearing stresses, and (2) their cause, deep-seated flow.

[16] See, for instance, the highly local conglomerate of the Cretaceous Panoche formation on the east side of the Mount Hamilton block, in the latitude of Monterey Bay (best exposed on Quinto Creek). These conglomerates are nearly five thousand feet thick and thin out rapidly both north and south. On the west side they are cut off from the Mount Hamilton block by a major fault. The materials of the pebbles were clearly derived from the Franciscan and pre-Franciscan rocks of the adjoining Mount Hamilton and Gabilan blocks. B. L. Clark, "Tectonics of the Valle Grande of California," *op. cit.*, pp. 228-9 and 237.

[17] Compare the large *Fault Map of the State of California* which was issued in 1922 by the Seismological Society of America on the scale of 1:506,880, about 8½ times that of the linear scale of Clark's little sketch map. The faults on that map were compiled by Bailey Willis and H. O. Wood. What differences there are, are largely the result of different emphasis.

Reid's keen analysis of the forces that produced the results manifest after the earthquake of 1906 will remain for a long time to come a classic worthy of careful study. Let us follow that part of his reasoning which concerns us here.[18] In a diagram Reid shows graphically the distance through which points on both sides of the San Andreas fault moved suddenly at the time of the earthquake, occupying new positions and thereby relieving an accumulated strain. He showed that these sudden displacements were exactly such as would result from an elastic rebound. Students of "Structural Geology" will do well to repeat for themselves the "very simple experiments" with strips of stiff jelly between two pieces of wood by which he demonstrated this.[19] He then asked himself what grouping of forces would produce the four specific characteristics of the observed displacement: (a) Displacement was limited essentially to a horizontal plane; (b) it was such that lines at right angles to the fault that were straight before the earthquake assumed the characteristic curvature shown in Fig. 5, on page 16 of his paper. (c) Measurable displacement was limited to a zone extending only 6 or 8 kilometers from the fault which itself is 435 kilometers long. (d) Displacement was relatively northward on the west side and southward on the east side. (e) The faulting produced no gaping fissures.

(a) Shows that the pair of opposing forces must have acted in a horizontal direction. From (d) it follows that the forces must have been of the nature of shearing forces, that is, they must have acted either at an angle to the (vertical) fault or parallel with it. (e) Excludes tensional forces. Reid then shows that the condition specified under (b) can result from shearing forces acting parallel to the fault only if they are active below the faulted layer and have their effect transmitted upward by friction. Compressive forces acting directly on the fault plane at an angle ($\pm$ 45°), would produce the same result.

[18] H. F. Reid, "Report of the State Earthquake Investigation Commission," Vol. II, "The Mechanics of the Earthquake," *Carnegie Inst., Washington, Pub. 87*, Vol. II, 1910, pp. 16-28. See also H. F. Reid, "The Elastic Rebound Theory of Earthquakes," *Bull. Dept. Geol. Univ. California*, Vol. 6, 1911, pp. 413-44.

[19] *op. cit.*, pp. 19-20.

Reid had to look for evidence that would allow him to decide which of these two possible types of forces actually was responsible, shearing forces active at depth below the faulted outer crust, or compressive forces active within it.

The answer seemed simple enough: "The elastic distortion accompanying a compression which could produce a fracture 435 kilometers long would not have been restricted to a zone extending only 6 or 8 kilometers from the fault plane."[20] He decided, therefore, in favor of subcrustal flow, probably resulting from isostatic conditions, as the cause of the San Andreas fault with the attending earthquake.

The emphasis in this argument lies on the word "produce." But in the meanwhile the great age of the San Andreas fault has been recognized more and more.[21] If this fault had already been in existence and had functioned frequently in the past, the relief from the regional strain at the time of the last earthquake need not have depended on the limiting strength of the rocks, as Reid assumes,[22] but would have occurred when the growing shearing force had reached the value of the resisting forces of friction. In such a case the elastic distortion would have been limited to a narrow zone along the fault. This destroys the argument against the primary forces acting within the crust itself. In view of this it cannot be said that Reid has made it "clear that the forces which moved the earth's crust in the region affected (by the last earthquake) were applied to its under side."[23]

But more than that. If the fault dates back to early Tertiary, if not Cretaceous, time there is no compelling reason why one should assume that the sort of stress which caused the movement during the last earthquake is in any way related to the stresses that created the original fracture.

[20] *op. cit.*, p. 23. Reid also thought that "the surveys, although not entirely decisive, are against a north-south compression." This statement has been proven to be untenable.

[21] Willis goes so far as to declare that: "We may regard the San Andreas fault as one of the oldest structures, if not the original structural feature, of California." (Bailey Willis, "Folding or Shearing, Which?," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 11, 1927, pp. 34 and 35.) Whether this one major fault deserves such an exalted estimate or not, there can be no doubt that it greatly antedated the particular earthquake upon which Reid's reasoning was based.

[22] *op. cit.*, p. 27.

[23] A. C. Lawson, "The Mobility of the Coast Ranges of California," *Bull. Dept. Geol. Univ. California*, Vol. 12, 1921, p. 432.

The fault pattern of the Coast Ranges and its interpretation. After all, the San Andreas fault is but one major line of faulting in a system of fractures which should bear the evidence of its origin written in its pattern. This consists essentially of a few major fracture lines of great length which tend to be parallel for long distances, from which minor oblique fractures branch off at intervals dividing the Coast Ranges into wedge-shaped blocks.[24] The pattern may, therefore, be said to consist of "pinnate fractures" ("Fiederspalten") as H. Cloos has called them,[25] likening the minor faults which branch off at a constant angle to the barbs on the shaft of a feather.

All pinnate fractures indicate differential movement and resulting rotational stresses. But the nature of the deformation which resulted in the movement may be widely different in different cases.

Thus excellent pinnate fractures form when a glass plate is subjected to torsion, as in Daubrée's classical experiment.[26] Here the essential forces act in three dimensions. In the case of differential flow the deformation is confined to two dimensions. The oblique fractures along the edge of a glacier or of a mudflow belong to this type. The same is true when differential movement is transmitted to the crust from below. The faults *en échelon* of Oklahoma (Fig. 73, p. 252), for instance, would undoubtedly have been changed into pinnate fractures if the differential movement had been carried farther. For in that case major fractures would have developed, tearing through parallel to the direction of movement.[27]

In all these cases the "barb" fractures arise first or at least simultaneously with the major or "shaft" fractures, and, correspondingly, they are present in large numbers. In the latter respect they differ in an important way from the fault pattern of central California. There the major fault zones dominate the pattern. They are of great length. The most famous, the San Andreas fault, for instance, can be traced

[24] Bailey Willis, "Folding or Shearing, Which?" *Bull. Am. Assoc. Petrol. Geol.*, Vol. II, 1927, p. 36.

[25] Hans Cloos, "Bau und Bewegung der Gebirge in Nordamerika, Skandinavien und Mitteleuropa," *Fortschritte der Geologie und Palaeontologie*, Bd. 7, H. 21, 1928, pp. 253-4.

[26] A. Daubrée, *Études synthétiques de Géologie Expérimentale*, Paris, 1879, Pl. II.

[27] For an instructive experiment see Ernst Cloos, "Feather Joints as Indicators of the Direction of Movement on Faults, Thrusts, Joints, and Magmatic Contacts," *Proc. Nat. Acad. Sci.*, Vol. 18, 1932, pp. 387-95.

for a distance of six hundred miles.[28] Compared with such lengths, the width of each fault zone (or "rift") is very small indeed. Compared with these major fracture zones, the oblique "barb" fractures are so few and irregularly spaced that the writer considers it improbable that they represent the type of pinnate fractures which arise from *en échelon* fractures due to differential movements of the crust or the subcrust.

This view is strengthened by two further observations: (a) The oblique "barb" fractures are of different ages, some being much younger than others. (b) If the "barb" fractures are the result of rotational strain set up by differential movements of adjoining blocks, the direction of movement can be read directly from the angle at which the "barb fractures" join the major fracture zones. In each case the landward block should have moved northwestward with reference to the adjoining seaward block. This is the direct opposite of the differential movement actually observed along the major fault zones.

For these reasons, the writer considers it probable that the major fault zones or "rifts" of central California arose originally as tension fractures, similar to such zones as the Balcones and Mexia fault zones, and that the oblique "barb" fractures resulted secondarily from torsional deformation of the narrow blocks bounded by the major "rift."

The original major fault zones must have been modified by subsequent epochs of regional compression. They differ from typical tensional fault zones in three ways:

(1) Their traces represent remarkably smooth lines practically free from angular, local kinks.

(2) Their courses are marked by a broad zone of crushing which form conspicuous linear depressions in the landscape as they waste away faster than the uncrushed rock under regional denudation.

(3) They bear evidence of considerable recent horizontal movement along the faults, such as was actually observed during the earthquake of 1906.

To the writer all three peculiarities seem to follow directly from the interpretation given above. Tensional fractures invariably show ir-

[28] From the Mexican boundary to Punta Arenas.

regular jagged traces. Later tangential movements along such faults are possible only if the pressures are sufficient to shear off the projections creating a zone of sheared and crushed rock in place of the jagged original fracture. Thus, to the writer, the three peculiarities listed above actually seem to demand for their explanation that the major fractures in the Coast Ranges came into existence as tensional fractures in a phase of crustal tension and that their special peculiarities were superimposed on them in subsequent phases of crustal compression.

But why the horizontal movement along major fault planes in the Californian Coast Ranges? Movement results from unbalanced forces. If the outer shell of the earth were uniform in thickness and material, all horizontal stresses would be balanced and movement would be possible only radially outward (i.e., upward). Horizontal movement, therefore, must be due to lack of uniformity in either thickness of the crust or materials or both, in a horizontal direction. Major faults of California along which horizontal movement is definitely proved, run out on the edge of the continental shelf, in a northwesterly direction. There a small part of the horizontal stresses in the outermost two miles of the crust is left unbalanced. The resulting movement under crustal compression should be toward the northwest on the seaward side of the blocks, which is the direction of movement actually observed. In addition, the individual long, narrow blocks between the major fractures are subdivided into deep sediment-filled troughs and high blocks which carry the crystalline substructure close to the surface. Crustal compression must vary correspondingly in different directions and must lead to local yielding in such a way that horizontal movement along the blocks becomes possible.

Results of precise triangulation. It is generally assumed that the resurveying of the triangulation net in Central California after the earthquake of 1906 has demonstrated a regional strain which must be the result of "a persistent northerly subcrustal flow." Lawson, who used this expression in his paper on "The Mobility of the Coast Ranges of California," emphasized again that a fundamental weakness attaches to the data upon which all discussion of Californian earth movements must be based. This is the assumption that the two

stations, Mount Diablo and Mocho, which mark the base-line for all the computations in Hayford and Baldwin's original report, had remained unchanged since the first triangulation between 1852 and 1891. These two points lie only about 32 miles east of the San Andreas fault. Recognizing this source of uncertainty, Dr. A. L. Day, as chairman of the committee on seismology of the Geophysical Laboratory, requested the U.S. Coast and Geodetic Survey to reoccupy the precise triangulation stations of California and to compute the changes in geographic positions on the assumption that two stations in the Sierra Nevada had remained unaffected by the recent earth movements. These two stations, Mount Lola and Round Top, lie 150 and 160 miles east of the San Andreas fault. In 1924 Bowie published a preliminary report of new observations.[29]

The data on which this report was based were, unfortunately, incomplete. The exhaustion of congressional appropriations in 1924 had prevented the closing of a gap of about sixty miles between the northern and the southern halves of the net of triangulation. When this gap was closed two years later, and the final check was applied to all measurements, small instrumental errors were found to have accumulated to such an extent that the preliminary results published in 1924 were largely wrong.

The final results were published by Bowie in 1928.[30] They prove conclusively that there has been no northwestward "drift" of the seaward side of the fault zone. There have been no certain progressive changes in the position of triangulation stations in central and southern California at all except close to the fault line of the 1906 earthquake. And even there, only stations less than twenty miles from the fault show definite displacement.

This finding must be disappointing to those who have seen in California "indisputable" evidence of momentous subcrustal flows dominating the structural plan of the earth's crust. When viewed without

[29] William Bowie, "Earth Movements in California," *U.S. Coast and Geodetic Survey, Spec. Pub. 106* (Serial No. 273), 1924.

[30] *idem*, "Comparison of Old and New Triangulation in California," *U.S. Coast and Geodetic Survey, Special Pub. 151*, 1928. For a good summary of the whole triangulation work in California, see John R. Freeman, *Earthquake Damage and Earthquake Insurance*, New York, 1932, pp. 196-208. The supposed evidence of crustal creep derived from latitude observations at Ukiah is discussed by Walter D. Lambert, "An Investigation of the Latitude of Ukiah, California, and of the Motion of the Pole," *U.S. Coast and Geodetic Survey, Special Pub. 80*, 1922.

such a prejudice, the results do not seem surprising. The displacements shown on the maps of Bowie's report appear simply as the strains set up in the blocks between the major faults under the present conditions of crustal compression.

Interpretation continued. The interpretation of the cause of horizontal movements along major faults given above, covers also the intense local folding characteristic of the California Coast Ranges. During epochs of crustal compression, compressive stresses act on each point within the crust from all directions. In the case of a heterogeneous mobile belt, the deformations that result receive direction from the differences in strength that exist in the outermost part of the crust within the individual blocks. Positive blocks are squeezed up and overthrust onto the edges of lower blocks. This produces intense compression within the thick sediments of negative blocks. Recent experiments conducted in the department of Muskingum College have shown what irregular trends may result from compression of wedge-shaped blocks.[31] Rotational deformation, such as Vickery has postulated for the Livermore block,[32] may also have played a rôle in many blocks.

The general view of orogenesis developed in these pages demands evidence of geosynclinal phases during which the crust stood under tension. For the Coast Ranges such tensional phases seem to have been assumed by all workers, although they were not generally clearly recognized as such. Willis, for instance, speaks of them in the following terms: "There have been periods of deformation separated by periods of quiescence. During the latter, the relief of the surface of the fault mosaic was reduced by erosion of the highs and sedimentation in the lows. It is possible also that relaxation of the horizontal pressure may have caused gravitative subsidence of the previously compressed and elevated ranges, permitting widespread deposition over the basement of the fault mosaic."[33] This expression "relaxation of the horizontal pressure" is frequently used to explain such changes in an opposite sense. Those who have followed carefully the detailed descriptions of reversals of movement along faults given in the pre-

[31] R. H. Mitchell, "Arcuate Mountains Produced by Modification of Stone's Structure Machine," *Science*, Vol. 72, 1930, pp. 275-6, esp. Fig. 2.

[32] F. P. Vickery, "The Structural Dynamics of the Livermore Region," *Jour. Geol.*, Vol. 33, 1925, pp. 608-28.

[33] Bailey Willis, "Folding or Shearing, Which?," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 11, 1927, p. 37.

ceding descriptions of Coast Range structure, will have a clear picture of the magnitude of the changes involved. Continuous pressure, even though it be variable in intensity, can never lead to the great rearrangements of blocks which have taken place again and again when sedimentation was resumed after an epoch of compression. What we see can be understood only if we assume that during periods of sedimentation the compressive stress first approached zero and then became negative, leading to a distention of the whole region which brought about a readjustment of blocks.

Clark, in fact, arrived at precisely this picture through an analysis of Coast Range structure without any previous hypothetical bias. He writes:

"It seems probable that many of the primary faults in the Coast Ranges were normal and tensional faults during much of Cretaceous and Tertiary times. Most of them, at the time of the Coast Range revolution, became compressional reverse faults; some of which developed into great thrusts. Some of those that were compressional in early Pleistocene time appear to be normal now. This alternation from normal to compressional, and then possibly a reversal to normal brought about some very marked reversals of movement of the blocks along those lines."[34]

Volcanic products are characteristic constituents of Coast Range stratigraphy and structure beginning with Miocene time. Much of the volcanic activity seems to have been associated with the "geosynclinal" phases of sedimentation. But with the great localization of stresses indicated by observation and demanded by theory, magmatic bodies may have come into existence or may have been set in motion at all stages of Coast Range deformation.

Here, then, we have an extreme development of the "heterogeneous" type of mobile belt. Between the local welts and furrows there exist the same structural relations that we have found on a larger scale in the "homogeneous" belts. An extreme crushing and shearing is a well known characteristic of many of the structurally high blocks. Along their borders, marginal folding was produced under diverse mechanical conditions.

[34] Bruce L. Clark, "Tectonics of the Coast Ranges of Middle California," *Bull. Geol. Soc. America*, Vol. 41, 1930, p. 794.

Where the upthrusting was sufficient, the margins were overthrust on top of the sediments of the adjoining low blocks. This overthrusting may be directed outward on opposite sides of a block. On the north side of the San Bernardino Mountains, for instance, gneissoid granite of doubtful Jurassic age may be seen thrust on top of late Miocene or Pliocene coarse terrestrial sandstones. According to Woodford and Harriss, this thrust plane dips 19° to 23° southwest, into the mountain.[35] A second thrust fault of similar dip lies immediately above it. Here Mississippian limestone is thrust onto the Jurassic (?) gneissoid granite. Near the foot of the range, a third, much steeper thrust fault dips about 80° into the mountain. Here the granite is thrown onto the same late Tertiary sediments as in the low-angle thrust fault higher up on the mountain slope.

On the opposite side of the San Bernardino Mountains, some twenty-five miles to the south, Vaughan observed similar overthrust relations. Here schists are thrust upon late Pliocene terrestrial sediments. One thrust fault, just west of Stubby Canyon, dips 70° north. Some six miles to the east, a similar thrust fault dips north at an angle of 65°.[36] On both sides these thrust faults are associated with "normal" faults along which the actual movement was clearly one of uplift of the mountain mass.

Such more or less local overthrusting from the rising toward the depressed block is characteristic of the Coast Ranges in general.[37] Any attempt to read into the thrust faults of the Coast Ranges a systematic dip from the ocean into the continent, such as Cloos, for instance, has taken over from earlier speculations, fails to grasp the real nature of the structural relations of this region.

[35] A. O. Woodford and T. F. Harriss, "Geology of Blackhawk Canyon, San Bernardino Mountains, California," *Bull. Dept. Geol. Univ. California,* Vol. 17, No. 8, 1928, pp. 265-304. See especially the fine photographs of this thrust fault on Pl. XL, and the map and structure section on Pl. XLI.

[36] F. E. Vaughan, "Geology of San Bernardino Mountains North of San Gorgonio Pass," *Bull. Dept. Geol. Univ. California,* Vol. 13, 1922, pp. 399 to 401, and map.

[37] For another good illustration see the map and discussion in Mason L. Hill, "Structure of the San Gabriel Mountains North of Los Angeles, California," *Bull. Dept. Geol. Univ. California,* Vol. 19, pp. 137-63; also N. L. Taliaferro, F. J. Hudson, and W. N. Craddock, "The Oil Fields of Ventura County, California," *Bull. Am. Assoc. Petrol. Geol.,* Vol. 8, 1924, pp. 802-3 and map, Pl. VII, opp. p. 789. See also the beautiful map in W. S. W. Kew, "Geology and Oil Resources of a Part of Los Angeles and Ventura Counties, California," *U.S. Geol. Survey, Bull 753,* 1924.

3. Heterogeneous Versus Homogeneous Mobile Belts

Looking back over this lengthy discussion of Coast Range structure, let us formulate clearly the differences between this heterogeneous type of mobile belts and that which we know in the Appalachian region, the homogeneous type. In the homogeneous mobile belt, facies and thickness of sediments remain constant over long distances, especially in a lengthwise direction. Changes in facies and thickness enter gradually. Folding is uniform over large areas. Welts and furrows run parallel over long distances. Unconformities and regional overlaps are generally inconspicuous and become evident chiefly when stratigraphic sections are compared over greater distances. They are regional rather than local in character. Normal faults and products of volcanic action are absent or rare.

In the heterogeneous mobile belts, on the other hand, conditions are exactly reversed. The thickness of sediments, and to a certain extent also the facies, are highly variable, along the length as well as the width of a belt. They change, often abruptly, within short distances. Welts and furrows form a mosaic. Folding is largely confined to the thick sediments of the depressed blocks. It is highly variable even within one block, bearing a definite relation to the borders of the adjoining elevated blocks, both in intensity and orientation. Unconformities and stratigraphic overlaps abound and are highly local features. Normal faults form a more or less definable pattern, some of them being an essential part of the block mosaic. Products of volcanic activity are present locally.

These two types of mobile belts obviously represent two extremes between which all possible transitions may be expected. The Colorado Front Range lent itself so well as an illustration of welt formation, because it combines properties of both types.

4. The Saxonian "Fault Folds"

The Harz Mountains, which we have used earlier in these pages as an example of welt deformation, represent but one of the structurally high blocks of the central German heterogeneous mobile belt. This region is roughly comprised between a line drawn in a northwest-southeast direction from the northwest end of the Teutoburger Wald to the west side of the Thüringer Wald and another line drawn parallel to it some distance east of Magdeburg. Toward the southeast,

the typical deformation of this belt vanishes as the Bohemian massifs are approached, say, roughly along a line connecting Weimar and Dresden. Toward the northeast it is lost beneath the Pleistocene cover. This region has been made classic through the studies of Stille. He has pictured it on a geologic-tectonic map on the scale 1 :250,000.[38] This is the region of the "Saxonian" orogenic movements. Through the unusually clear analysis in his paper of 1910, Stille has made it a type region for "Rahmenfaltung."[39] In our discussion of folding within the preexisting frame of older structures (pp. 159-60) we have already referred to it, without formally introducing the concept of the heterogeneous type of mobile belts.

Throughout this Saxonian orogenic belt all the essential features of our Coast Range structure are found. The region is characterized by the combination of folding with fracturing along nearly vertical faults, a combination "wie sie auf der Erde kaum ihres Gleichen hat."[40] As in the Coast Ranges, the major upthrown blocks are not merely passive blocks of a foundered crust, but are elongated in the direction of the axes of folding and partake somewhat of the nature of anticlines. Their borders are here and there overthrust onto the sediments of the depressed blocks. Yet the sediments on the upthrown blocks show little or no folding. In the downthrown blocks the intensity of folding grows with the thickness of the sediments.[41] The axes of the folds are the more nearly parallel to the margins of the surrounding upthrown blocks the thicker the sediments and the nearer the margins of the higher blocks.[42] Most overthrusts strike parallel to the dominant trend of the orogenic belt, that is, in a northwest-

[38] H. Stille, *Übersichtskarte der saxonischen Gebirgsbildung zwischen Vogelsberg-Rhön und der norddeutschen Tiefebene,"* 1 :250,000, Preuss. Geol. Landesanstalt, Berlin, 1922.

[39] *idem*, in "Mitteldeutsche Rahmenfaltung," *3. Jahresb. d. Niedersächs. Geol. Ver. Hannover*, 1910, pp. 141-69. With a very useful tectonic sketch map on the scale 1 :2,100,000.

[40] *ibid.*, p. 146.

[41] *ibid.*, p. 156. See also p. 160 above. For a discussion of the rôle of the thickness of sediments, especially of the Permian salt beds, in influencing the type of deformation in this region see H. Stille, "Injektivfaltung und damit zusammenhängende Erscheinungen," *Geol. Rundschau*, Vol. 8, 1917, pp. 90-142.

[42] H. Stille, *op. cit.*, 1910, p. 163.

southeast direction.[43] A large number of unconformities and their local presence and absence from place to place are as characteristic[44] here as in our Coast Ranges.

The explanation which we have applied to the Coast Ranges, seems to fit all known conditions in the Saxonian orogenic belt. It was, in fact, suggested for it by Schuh in 1922.[45] He pointed out that compression alone is not capable of producing a system of essentially vertical faults such as blocks out the mosaic of this region. The division into blocks must owe its origin to a process radically different from the compression which produced the folding and overthrusting. This can only have been regional tension. The actual structure of the Saxonian belt, then, would be the result of an alternation of epochs of tangential tension with others of tangential compression.

Stille, however, interprets the structure of the Saxonian orogenic belt in a very different way. His view grew out of the recognition that the fault blocks of this region were more than fractured and more or less collapsed portions of the crust, the view on which Suess had built his terms "horst" and "graben." He found that "in the 'block terrane' of Germany it is possible to recognize an arrangement of structures along certain lines of uplift and depression, just as in folded mountains the strata are elevated along certain lines (anticlinal axes) and depressed along others (synclinal axes)." This led him to think of this region which is so evidently dominated by nearly vertical faults, as a special type of folding "in which the folds, in contrast to the normal type of folding, are allied in a strong degree, already in *statu nascendi*, with faults." He introduces the term "fault folds" (Bruchfalten") for this type which is "intermediate . . . between true folds and block faults."[46]

Stille then holds that "fault folds," like normal folds, result from the action of crustal compression and represent a modification due to

[43] H. Stille, "Beitrag zu Frage der Saxonischen Zerrungen," *Nachricht. d. Ges. Wiss. Göttingen, Math.-phys. Kl.*, 1925, pp. 178-83. Of 37 thrusts reported in the Saxonian belt, 33 trend northwest-southeast.

[44] For a good local description of these conditions see, e.g., O. Grupe, "Die Einzelphasen der saxonischen Gebirgsbildung am Deister," *Jahrb. Preuss. Geol. Landesanstalt für 1926*, Vol. 47, Heft 1, pp. 357-82.

[45] F. Schuh, "Die saxonische Gebirgsbildung," in *Kali,* Vol. 16, 1922, Heft 8, 9, 15, 16.

[46] H. Stille, "The Upthrust of the Salt Masses of Germany," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 9, 1925, p. 420.

physical differences in the crust. There are two serious objections to this view. One has been raised by Schuh and others. Compression alone cannot break up a section of the earth's crust over one hundred miles wide and over two hundred miles long into a mosaic of fault blocks typically bounded by "normal" faults. "Normal" faults may, of course, arise locally in the course of crustal compression under all sorts of conditions. But no mechanism is known to the writer by which compression could produce systematic results of this type over such an area as that of the Saxonian "fault folds."

The other objection arises when we view the Saxonian "block terrane" in its relation to the rest of central Europe. Its fracture lines are by no means a specific part of this orogenic zone. They are part of a system of "normal" fractures which cut across the Paleozoic structures of central Europe from the Black Forest in the southwest to the northeast side of the Silesian Mountains in the northeast, and from the Danube between Regensburg and Passau in the south to the Flechtinger Höhenzug near Magdeburg in the north.[47]

Outside the Saxonian "block terrane" there can be no doubt that fracturing was the dominant effect. Folding is absent or purely incidental. Typical tension fractures without compressional folding are found even within the region of the Saxonian "fault folds."[48] To set off one group of fractures against the rest as being genetically conditioned by orogenic movements means obviously doing violence to plain facts.[49]

To the writer it seems that all known structural relations connected with this northwest-southeast system of fractures are naturally explained when the fractures are interpreted as the result of phases of regional tension. The local folding and allied features, pointing to crustal shortening, would then be the result of compressional phases. The Saxonian "block terrane" would differ from the rest of frac-

[47] For a brief summary see E. Suess, *The Face of the Earth* (trans. by Sollas and Sollas), Vol. IV, pp. 34-40.

[48] e.g., the Allertal Graben, on the west side of the Flechtinger Höhenzug, according to the interpretation by P. Woldstedt, in his paper "Tangential Salzfaltung oder vertikaler Salzauftrieb?" in *N. Jahrb. f. Min., etc.,* Beil. Band 58, Abt. B., 1927, pp. 598-605.

[49] "It can hardly be doubted that all these lines of dislocation, possessing so many characters in common, must have a common origin independent of the Variscan folding," E. Suess, *op. cit.,* p. 39.

tured central Europe not by a different history, but by greater mobility.

Regional tension created the basins and furrows which became the sites of sedimentation in Mesozoic and Cenozoic time, while the epochs of crustal compression forced up the "positive" units. The overthrusting along the borders of some of the great "positive units," such as, for instance, along the Great Elbe fracture or on the southwestern edge of the Bohemian mass, outside the Saxonian "block terrane," is the exact counterpart to the overthrusting along the southwest side of the Thüringer Wald or the northeast side of the Harz Mountains. All are the result of regional compression, crustal "crowding," while the numerous grabens and normal fractures point to regional tension as their cause.

There are, consequently, all gradations between regions in which both pulling apart and pushing together have been effective and those where tension fracturing dominated greatly. Thus faulted[50] belts of high mobility ("heterogeneous mobile belts") grade into unfaulted belts of high mobility ("homogeneous mobile belts") on the one hand, and into faulted belts of low mobility on the other.

II. FRACTURE BELTS OF LOW MOBILITY

1. The East African Rift Valleys

The most striking examples of what are here called faulted belts of low mobility are the great zones of fault troughs or "rift valleys," as J. W. Gregory has called them.[51] The belt of fracturing of which the great rift valleys of Africa are the most conspicuous portions, extends from the Lebanon in northern Palestine to the Sabi River in southern Africa, over a distance which is more than one-sixth of the circumference of the earth. The rift valleys are by no means continuous throughout this length. The chains of grabens are only the most conspicuous expression of a wide belt of fracturing which at its northern end reaches from the Gulf of Aden to the Gulf of Suez, and

[50] The word "faulting" is here used in the sense of "tension faulting" which includes all forms of fracturing in which active regional tension plays a part, such as fracturing under torsion, in contrast to thrust-faulting, which cannot be developed regionally under active tension.

[51] ". . . using the term 'rift' in the sense of a relatively narrow space due to subsidence between parallel fractures." J. W. Gregory, *The Rift Valleys and Geology of East Africa*, London, 1921, p. 18.

in its southern half from Lake Nyasa to the grabens of southeastern Belgian Congo (Lake Upemba). Throughout this enormous extent, structures typical of crustal compression are absent or at least entirely subordinate to the results of tension.

The fault pattern: evidence of tension. The crucial criteria concerning the nature of the forces that have produced the geological structures here, as always, are found in the details of structure. Fig. 83[52] shows the alignment of the fractures in the East African belt

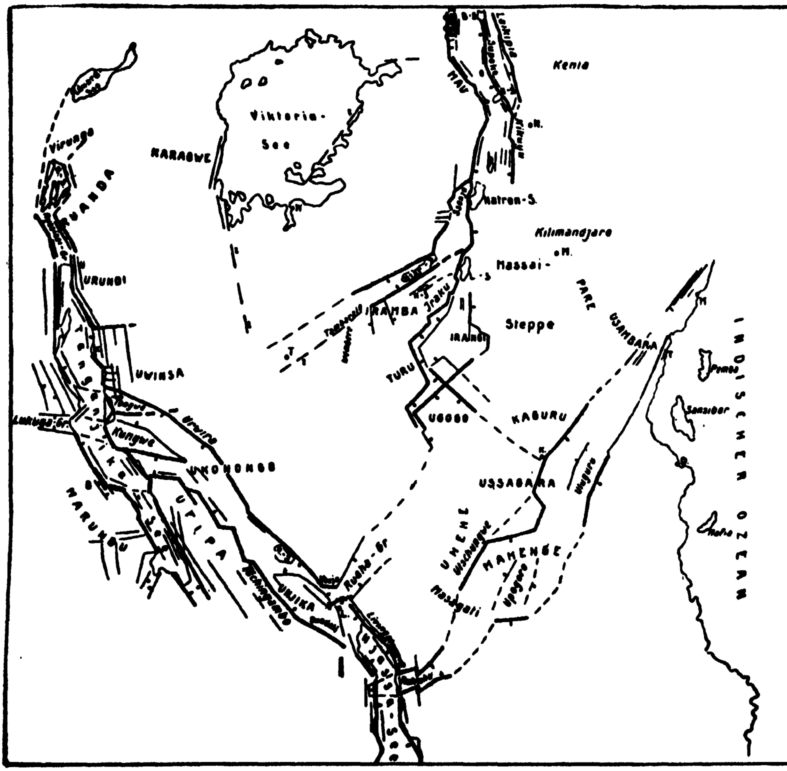


Fig. 83. Tectonic sketch map showing lines of faulting in the region of the rift valleys of eastern Africa. Major and minor faults distinguished by heavy and light lines. Dashed lines = suspected faults. Arrows indicate downthrow side.

(E. Krenkel, 1922; reproduced from *Die Bruchzonen Ostafrikas*, by permission of Verlagsbuchhandlung Gebrüder Borntraeger)

[52] Reproduced from Pl. 1 (opp. p. 16) in E. Krenkel, *Die Bruchzonen Ostafrikas*, Berlin, 1922.

of rift valleys. The angular zigzag pattern is characteristic of fracturing under tension. Such a pattern cannot be produced by compression alone.[53]

The details of the faulting within the rift valleys correspond to the larger pattern. Here longitudinal fractures dominate, of course. Speaking of the Great Rift Valley of Kenya Colony, Gregory says: "Between the two boundary faults are numerous crowded parallel faults, arranged like a grid." One such "fault-grid occurs west of the Lower Kedong [about 40 miles southwest of Nairobi], where eight parallel faults occur in a width of little over a mile. The same structure occurs on a much larger scale south of [the volcanoes] Suswa and Soit Amut [about 35 miles northwest of Nairobi]. . . . The floor of the Rift Valley is also interrupted by long fault blocks or horsts, left upstanding by the subsidence of the ground around them. A chain of these horsts occurs, for example, east of Lake Nakuru and [the volcanic caldron of] Menengai [about 85 miles north-northwest of Nairobi]. Striking examples of them, especially long and narrow, rise above the alluvium around Lake Magadi [about 55 miles southwest of Nairobi], and form the long north to south peninsulas on the shores of that lake. . . . The chief faults within the Rift Valley trend north and south, but it is also intersected by transverse movements that divide the valley into basins."[54]

Evidence of compression. All attempts to interpret the East African rift valleys as the product of crustal compression have dealt with them in generalized terms. They are based on two kinds of observations. On the one hand, there is the physiographic evidence of up-arching along the margins of the rift valleys.[55] Marginal welts are not universally present, but a glance at a good orographic map of Africa shows that they are striking features in most cases. Frequently the

[53] Bailey Willis' diagrams illustrating his concept of "ramps" always show cross-sections only, even when they are block diagrams. None show a regard for the surface trace of the "ramp." It does not seem possible to produce by compression alone a fracture showing a relatively regular zigzag pattern in a horizontal plane in which the dimensions of the zigzag are of the same order of magnitude as the thickness of the crust. (See Bailey Willis and Robin Willis, *Geologic Structures*, New York, 1929, pp. 80-100.)

[54] J. W. Gregory, *The Rift Valleys and Geology of East Africa*, London, 1921, pp. 215-16.

[55] See, e.g., the chapter on "Use of Physiographic Features" in Bailey Willis, "Dead Sea Problems: Rift Valley or Ramp Valley?," *Bull. Geol. Soc. America*, Vol. 39, 1928, pp. 502-6.

highest elevations lie closest to the deep furrows. It was this fact which the African rift valleys share with most others that caused us to introduce the neutral terms "welt" and "furrow" at the beginning of this book. The German equivalent of "welt" has long been used for these arched-up margins ("Randwülste" or "labiale Aufwulstungen").[56]

The highest of these marginal welts is that of the Ruwenzori Range which reaches a height of 16,794 feet. This narrow, snow-covered range of pre-Cambrian crystallines rises abruptly between the grabens of the Semliki Valley to the west and that of the Toru Valley on the east. It is a marginal welt to two deep rifts. This may have favored its abnormal uplift. It should be noted that while in height it compares with folded mountains, it appears to be a short, narrow wedge block such as characterizes the fracture belts and not the zones of folding.

Besides this very general physiographic condition, some local structures were observed which seemed incompatible with a tensional origin of the rift valleys. Wayland, for instance, was impressed with what seemed to be evidence of horizontal displacement between opposite sides of the Lake Albert rift valley.[57] Lateral displacement of from 11 to 15 miles can only be accomplished by regional compression of a magnitude which seems incompatible with the almost universal presence of "normal" faults. Wayland, therefore, takes refuge in the assumption that below the surface all border faults of rift valleys are thrust faults. The visible normal faults he explains as the result of settling under the action of gravity of the projecting wedge-shaped edges of the rising thrust blocks.[58]

The observations on which Wayland bases his argument, so far as the writer can see, do not prove that there actually was any lateral movement. They certainly do not justify the substitution of purely hypothetical thrusts for the almost universally visible normal faults.

Two considerations, moreover, prove Wayland's interpretation impossible: (1) Nowhere from the Zambesi to the Jordan has any

[56] E. Krenkel, *Die Bruchzonen Ostafrikas*, Berlin, 1922, p. 165.

[57] E. J. Wayland, "Some Account of the Geology of the Lake Albert Rift Valley," *Geog. Jour.*, Vol. 58, 1921, pp. 344-59.

[58] His diagrams were reproduced by Bailey Willis and Robin Willis in *Geologic Structures*, 2nd ed., New York, 1929, p. 99.

folding been observed of the character and magnitude that we see achieved in the Californian Coast Ranges where the evidence for horizontal displacements of similar order of magnitude is quite convincing.[59] Yet in the Californian Coast Ranges the dominant faults are essentially vertical. Wherever there is overthrusting, folding of varying intensity is associated with it locally. If the rift valleys were bounded by thrust faults and owed their origin to compression, comparable signs of compression should exist. They are lacking completely.

(2) The other objection to Wayland's views arises again from the ground plan of the "normal" faults. They are fracture lines that may be traced for miles in a straight line. Nowhere in the world has settling of rock materials along an oversteepened front produced continuous straight cracks. Such settling always starts along some point and produces fractures that are sharply curved. This is true whether the settling takes the form of a rock fall in solid rock or of an earth flow in loose materials. It is inconceivable that along an oversteepened front several miles in length stress conditions due to gravity should be so nearly alike that a crack started at one point could prolongate itself along a straight line generally even at an angle to the "grain" of the rock.[60]

Mechanics of the fault pattern. Granting, then, that crustal tension played an essential part in the formation of this gigantic belt of fracturing, we must ask ourselves what part it played. Gregory's "keystone" hypothesis is mechanically impossible. "The first stage in the development of the rift valley was the formation of a low, broad arch trending north and south. Then the weakening of the supports led to the collapse of the keystones along the top of this

[59] F. P. Vickery, "The Structural Dynamics of the Livermore Region," *Jour. Geol.*, Vol. 33, 1925, p. 612 (horizontal shift of 12 miles); L. F. Noble, "The San Andreas Rift and Some Other Active Faults in the Desert Region of Southeastern California," *Carnegie Inst., Washington, Year Book 25*, 1925-1926, p. 420; R. J. Russell, "Recent Horizontal Offsets along the Haywards Fault," *Jour. Geol.*, Vol. 34, 1926, pp. 507-11.

[60] No known facts of geology permit us to assume that upward movement along any thrust faults took place at such a rate that an "overhang" of the valley sides was created sufficient to produce the straight and long fault blocks which skirt the sides of the rift valleys at so many places. See Wayland, *op. cit.*, p. 358: "The controlling factors of alignment are first, overhang (itself straight), and, second, tensile differences at surface."

arch. . . ."[61] Even the beginning of the first sentence of this quotation from Gregory's latest book does not express a necessary conclusion drawn from known facts. In fact, Krenkel's account of the steps in the formation of the typical African rift valley begins with the exactly opposite statement: "At first a shallow, broad depression of great length is formed. . . ."[62]

The only concrete fact from which we can reason is the zigzag form of the major faults, as seen in ground plan, coupled with a tendency to a vertical attitude of the fault planes. Such a zigzag pattern gives one the impression of a major fracture line that established itself in its own proper direction across a surface covered with a network of preexisting minor fractures such as systems of jointing or with other structural inequalities giving a "grain" to the country.

Gregory recognizes in the irregularity in the course of the western branch of the African fracture zones to the effect of the "structural grain of the country" which the rift valleys intersect at various angles in their curved course. "Although small-scaled maps demonstrate the continuity of the valley, more detailed examination shows that the long, straight, even scarps are broken by spurs and gaps, and the valley in places appears to consist of segments arranged *en échelon.*" This behavior he compares with that of a fracture across a plank of grained wood which "gives off overlapping branch cracks, or itself here and there alters its course to follow the grain."[63]

It seems probable that jointing plays a greater rôle in this connection than is generally recognized. Since Daubrée published the maps accompanying his experiments on joint systems, many papers have appeared in which attention was called to the way joint systems in table lands may control the pattern of drainage.[64] A certain amount of control is recognized to be almost universal. It seems only reasonable to assume that systems of master joints sufficiently pronounced to find expression in the drainage pattern of a map of but moderately

[61] J. W. Gregory, *The Rift Valleys and Geology of East Africa,* London, 1921, p. 24.

[62] E. Krenkel, *Die Bruchzonen Ostafrikas,* Berlin, 1922, p. 29.

[63] J. W. Gregory, *op. cit.,* pp. 268-9.

[64] Important literature quoted in J. D. Scott, "The Spacing of Fracture Systems and Its Influence on the Relief of the Land," *Gerlands Beitr. z. Geophysik,* Vol. 13, 1914, pp. 164-74, 241-59.

large scale should also influence the shape of the line along which the land surface will tear under regional tension.

East African fault system as a whole. Ever since the length and virtual continuity of the East African fracture systems had been recognized, they were accepted as evidence that this fracture belt "must have had a deep-seated, world-wide cause."[65] At least one other feature of these belts seems to indicate that they owe their formation to stresses which involved the crust in its whole thickness over a large segment of the earth, instead of being merely an accidental summation of purely local deformations. Any good topographic map of Africa shows a remarkable similarity between two conspicuous geographical lines.[66] One follows roughly the center of the belt which is marked by the Lakes Nyasa, Tanganyika, Kivu, Albert-Edward, and Albert. Running at first northward, this line bends rather abruptly northwestward with the northern end of Lake Nyasa and then swings from a northwesterly direction through north to northeast. Inserting one point of compasses a little northeast of Lake Manjara about eight hundred miles east of the north end of Lake Tanganyika, you will find that the curved part of this line lies roughly on a circle of a radius of eight hundred kilometers.

Then insert one point of the compasses out in the Indian Ocean about eight hundred miles due east of Daressalam. You will find that the stretch of the African east coast which lies between Cape Delgado and the mouth of the river Tana shows a curvature of the same radius. Both curves, moreover, are continued at their southern ends in straight lines running in a north-south direction.

These two lines are not parallel, but they present similar curves. Such similarity can hardly be a matter of pure coincidence. It seems more reasonable to see in it evidence that these lines represent major lines of tensional yielding which came into existence through the same large crustal stresses and were deflected for the same (unknown) reason.

[65] J. W. Gregory, *The Rift Valleys and Geology of East Africa*, London, 1921, p. 23.

[66] E. Krenkel, *Die Bruchzonen Ostafrikas*, Berlin, 1922, p. 171.

Volcanic activity. A map showing the areal grouping of Tertiary and Quaternary volcanics and lavas in eastern Africa[67] shows that no recognizable relation exists between the form of the rift valleys in ground plan or cross-section and the quantity and distribution of volcanic materials. There are none in the region of the great rift valleys of Lakes Nyasa and Tanganyika, while the rift belt east of Lake Victoria traverses a region of thick lava flows, from the strangely pitted region of the great caldron volcanoes in the south to Lake Rudolf and north to the trap sheets of Abyssinia. Volcanic activity clearly is not the cause of the fracturing.

Welts and furrows and degrees of mobility. The sinking of the bottoms of the rift valleys, according to the general views developed in these pages, is the result of a pulling apart of the crust during epochs of crustal tension. It differs from the formation of a geosynclinal furrow in a homogeneous mobile belt merely by the conspicuous faulting and its smaller width. Both may be explained as the result of less mobile behavior.

The raising of the marginal welts, on the other hand, is interpreted as the result of crustal compression. The vertical displacement effected is small compared with the elevations achieved along mobile belts. Folding along the margins of the rifts is purely local and rare. So are the few cases of overthrusting.[68] This again points to lower mobility.

Here, then, lies the ultimate justification for grouping elevations and depressions along belts of folding and of fracturing under the common terms "welts" and "furrows." All such belts, according to this view, owe their origin to world-wide crustal stresses. In both, "furrows" result from crustal tension, welts from compression. Where the furrows are deepest, the growth of welts seems to be facilitated and intensified.

Along some belts, furrows sink and widen under crustal tension without major fracturing. Along these same belts, welts rise without much "normal" fracturing and creep in large overthrusts toward the geosynclines, causing the long lines of parallel folds which char-

[67] See map, Fig. 9, p. 59, in E. Krenkel, *Die Bruchzonen Ostafrikas,* Berlin, 1922. Also, "Geologische Übersichtskarte des Mittleren Ostafrika," Pl. XXI, opp. p. 342, in E. Krenkel, *Geologie Afrikas,* Erster Teil, Berlin, 1925.

[68] e.g., quartzites thrust upon lavas of a young volcano, described by V. Uhlig, *Geogr. Zeitschr.,* Vol. 13, 1907, p. 489.

acterize the typical "folded" mountains. These are the "homogeneous" mobile belts.

In the "heterogeneous" mobile belts fracturing accompanies the formation of the first furrows. Here and there, sooner or later, these form avenues of intrusion and escape to the surface of liquefied crustal materials, magmas. The major normal fractures and the localized bodies of magma increase the inhomogeneity of the crust. The first epoch of compression produces a less regular distribution of welts. The next tensional phase increases the complexity and the result is a mosaic of blocks acting as welts and as furrows, localized folding and thrusting and all the intricacies of structure we see so well illustrated in our Coast Ranges, including the diversity of magmatic products. Some of these potential "heterogeneous" belts have never achieved a strong orogenic development and have remained essentially belts of fracturing.

In this sense, the three types, homogeneous and heterogeneous mobile belts and fracture belts of low mobility form a series of decreasing mobility, that is, of decreasing capacity for "plastic" behavior. Why should there be such a difference? The writer knows too little of the factors that determine the behavior of solids to suggest a concrete answer.

It is customary to speak of the crust being made more "rigid" by previous folding. It is difficult for the writer to see what that might mean. It is true that the heterogeneous belt of the Coast Ranges formed where the presumably "homogeneous" belt of the late Jurassic orogenesis had been. The earlier folding might be thought to have increased the "rigidity" of the surface along this belt. But the fracture system of eastern Africa came into existence where there had been no such earlier orogenic deformation. Furthermore, the crystalline foundation of the "homogeneous" Swiss Alpine belt is the same which in the Plateau Central of southern France behaved as a fracture zone of low mobility. The late Paleozoic orogenic history seems to have been exactly the same in both regions. The writer doubts if an explanation can be found in that direction.

It seems more likely that ultimately it will be found that not differences in the materials but differences in the distribution and rate of application of the stresses within the crust account for the different ways in which the crust reacts. This point may be illustrated by what

the writer learned when ten years ago he played with water freezing in spheres of glass and paraffin (see pp. 120-3). At low temperatures, with rapid freezing, dozens of cracks broke the thin walls of the glass spheres used. It was surprising to find that further freezing by no means widened all the closely spaced tension cracks on the surface as one should expect under absolutely uniform conditions. The further expansion of the surface was achieved by only a few cracks widening. Along these the water found its way to the outer surface and froze into welts of ice, while most of the other tension cracks remained unopened. Many showed not the slightest displacement on the surface. They could not be felt by running the hand over the surface and were visible only through the reflection of light along the walls of their capillary spaces. Immediately after the fracturing had occurred, the stresses within the thin glass shell became localized. As far as the writer can see, no one could have told just why the localization of stresses took the form it did take in each case. We must not be surprised if we are correspondingly unable to grasp the reasons why both the intensity and the rate of application of stresses varies so greatly along the belts of linear deformation of the earth's crust.

A localization of stresses along deep places of the furrows seems also to account for the greater height of welts immediately adjoining them. The same principle seems to be involved in Willis' observation that in his pressure-box experiments an initial kink in the profile of the surface of the compressed mass determined the location of an "anticline."[69] The broader principle involved was recently brought to the attention of geologists by a paper by Seidl.[70] Here, as in so many other aspects of the physics of materials, we are waiting for a comprehensive theoretical and experimental treatment which will give us the means of interpreting geological conditions in terms of clearly grasped principles and not merely of superficial analogies.

2. The Rift Valley of the Rhine

Views of origin. For a century the rift valley of the Rhine between Basel and Mainz has had a dominant influence on European thought concerning the origin of such structural troughs.

[69] See also R. W. Brown, "Experiments Relating to Factors Causing Localization of Folds," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 12, 1928, pp. 617-23.

[70] E. Seidl, "Kerbwirkung in Technik und Wissenschaft. Kerbwirkung in der Geologie," *Zeitschr. Deutsch. Geol. Ges.*, Vol. 77, 1925; Vol. 78, 1926.

The same hypotheses have been suggested in the past to explain the origin of the Rhine graben[71] that were advanced for the East African rift valleys. Gregory's keystone hypothesis was used by Elie de Beaumont for the Rhine graben in the first half of the last century. The idea that the visible normal faults along the borders of the rift valley are purely superficial effects of gravity along the outcrops of major thrust faults, which Wayland conceived in the field in Uganda, was published by Andreae for the Rhine Valley in 1887.[72] Suess seems to have been the first to recognize regional tension as the dominant factor in the making of such grabens. Recently Salomon, on the basis of detailed studies[73] on the origin of the Rhine graben extending through decades, has recognized the probability that both, tension and compression, must have contributed to the structure as we now see it.[74]

Details of structure. It is instructive to see how closely the Rhine graben parallels the rift valleys of Africa in all essential details. Fig. 84[75] shows the pattern of the faults along a small portion of the western border of the Rhine rift valley. It exhibits the same angularity and parallelism of faults. As in the African rift valleys, the

[71] L. van Werveke, "Die Enstehung des Mittelrheintales," *Mitt. Ges. f. Erdkunde*, Strassburg, 1923; M. Weber, "Zum Problem der Grabenbildung," *Zeitschr. Deutsch. Geol. Ges.*, Vol. 73, 1921, pp. 238-91.

[72] A. Andreae, "Eine theoretische Reflexion über die Richtung der Rheintalspalte . . . ," *Verh. Naturhist. Medic. Ver. Heidelberg*, N.F., Vol. 4, 1887, Heft 1.

[73] Salomon realized the need of quantitative information concerning the attitude in space of the secondary fractures—minor faults and joints—along the margin of the Rhine graben, which betray the stresses that have created the structure. He inspired and organized a series of detailed studies which have set a fine example for the kind of work which alone will ultimately lift geology to the full dignity of a "science." For reference to the publications by Dinu, Lind, Engstler, and Röhrer, which embody the results of these investigations, see W. Salomon, "Neue Kluft und Harnisch-Messungen im südlichen Odenwald," *Ber. Naturf. Ges. Freiburg*, Vol. 27, 1927.

[74] "Es kann also ein Graben ursprünglich infolge von Zerrung der Erdkruste mit nach unten konvergierenden Grenzspalten eingesunken sein. Nachträgliche Bewegungen können aber dazu führen, dass er dennoch später von den Seiten her überschoben wird. Das ist die mir bei dem jetzigen Stande unserer Kenntnis wahrscheinlichste Auffassung des oberrheinischen Grabens."—W. Salomon, *Grundzüge der Geologie*, Vol. I, 1924, p. 158.

[75] Redrawn from J. J. Dinu, "Geologische Untersuchungen der Beziehungen zwischen den Gesteinsspalten, der Tektonik und dem hydrographischen Netz im östlichen Pfälzerwalde (Hardt)," *Verh. Naturhist. Medic. Ver. Heidelberg*, Vol. 11, 1912, pp. 238-99, Pl. VII.

border faults of the Rhine graben are clearly deflected here and there by the "grain" of the country, as, for instance, where the west side cuts across the synclinal area of Zabern. This relation was emphasized especially by Reis and illustrated with a valuable map.[76]

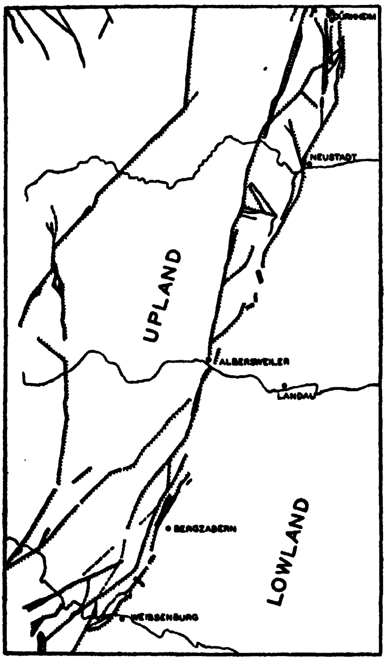


Fig. 84. Tectonic map showing the faults along the west side of the Rhine graben for a distance of 50 kilometers (30 miles) between the latitudes of Mannheim and Karlsruhe.

(Redrawn from Dinu, 1912)

The area between the border faults is here also split up into a grid or mosaic of blocks, some standing higher as "horsts," others dropped lower as "grabens." This is well shown by the detailed information obtained through the intensive drilling in the oil region of Pechelbronn,[77] about twenty-five miles north of Strasbourg, and the potash salt district, some ten miles north of Mulhouse.[78]

The structure shown by the drill is of sufficient significance to be here illustrated in Fig. 85.[79]

The sediments of the Rhine graben dip southeast, toward the

[76] O. M. Reis, "Der Rheintalgraben," *Geognost. Jahreshefte,* Vol. 27, 1914 (1915), pp. 249-68. See especially the map on Pl. 12.

[77] See, e.g., J. O. Haas, "La Stratigraphie et la tectonique des terrains tertiaires de Pechelbronne," *Bull. Assoc. Philom. d'Alsace,* Vol. 6, 1922. American readers will find most accessible the map and cross-sections in the recent paper by J. O. Haas and C. R. Hoffmann, "Temperature Gradient in Pechelbronn Oil-Bearing Region, Lower Alsace," *Bull. Am. Assoc. Petrol. Geol.,* Vol. 13, 1929, pp. 1257-73.

[78] See, e.g., the fine cross-section on Pl. XIII of L. van Werveke, "Tektonische Vorgänge zur Zeit der Entstehung unserer Steinsalz und Kalisalzlagerstätten," *Mitt. Philomath. Ges. Els.-Lothr.,* Vol. 4, Heft 4, Jahr. 1911, Strassburg, 1912.

Other references down to 1912 in B. Förster, "Die geologischen Verhältnisse der Kalisalzlager im Oberelsass," *Jahresb. u. Mitt. d. oberrhein. Geol. Ver.,* N.F., Vol. 2, 1912, pp. 21-5.

[79] Reproduced from H. Cloos, "Zur experimentalen Tektonik," in *Die Naturwissenschaften,* Vol. 19, 1931, Fig. 1, p. 242.

center of the graben with very gentle angles. The main border fracture also dips southeastward. On the other hand, the subsidiary fractures within the graben dip toward the northwest. This is precisely the arrangement of fractures which Cloos obtained in his experiments

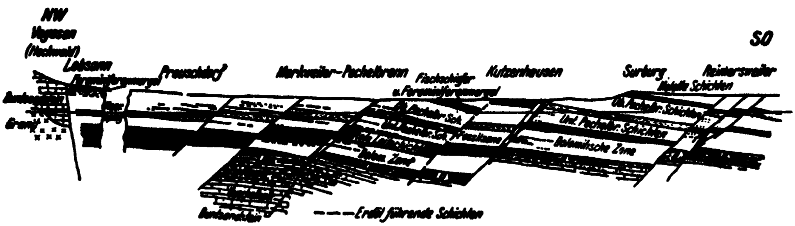


Fig. 85. Structure-section showing a part of the rift valley of the Rhine along its western border; drawn across the oil district of Pechelbronn (Alsace).

Note: (1) The main border fault along the foot of the Vosges Mountains, dipping steeply southeastward. (Dip inferred, probably not as steep in nature.) (2) The secondary faults dipping in a sense opposite to that of the main fault ("antithetic"). (Structural details accurate, based on drill records.)

(H. Cloos, 1931, from Haas and W. Wagner)

with wet clay. Fig. 86[80] shows the result of one of his experiments in which the relatively thin layer of clay was subject to tension by the method described on pages 144-5.

In this and in similar experiments, the structural pattern has been reproduced so accurately that they may be considered valid proof of the tensional origin of the Rhine and similar rift valleys.

In this rift valley, in which the fault blocks of the bottom lie covered by many thousands of feet of marine and freshwater sediments, accurate information is lacking as to where the deepest places are located. Yet it is at least worthy of note that the potash and rock salt deposits which for their formation required deep localized sinking, lie exactly on a line which connects the highest elevations of the welts on both sides of the graben, in the Vosges Mountains and in the Black Forest. In this area, furthermore, thick Tertiary sediments lie close to one side. In the well drilled areas along the west side of the valley, the Oligocene formations alone reach a thickness of six thousand feet. This is many times the thickness of the sediments of similar

[80] Reproduced from H. Cloos, *op. cit.*, Fig. 2, p. 243. See also paper of similar title in *Die Naturwissenschaften*, Vol. 18, 1930, pp. 714-47. Also H. Cloos, "Uber antithetische Bewegungen," *Geol. Rundschau*, 1928, pp. 246-51.

age found along the edge of the graben farther north. It looks at least as though here also very deep, if not the deepest, depressions hugged the edges of the graben close to the highest welts.

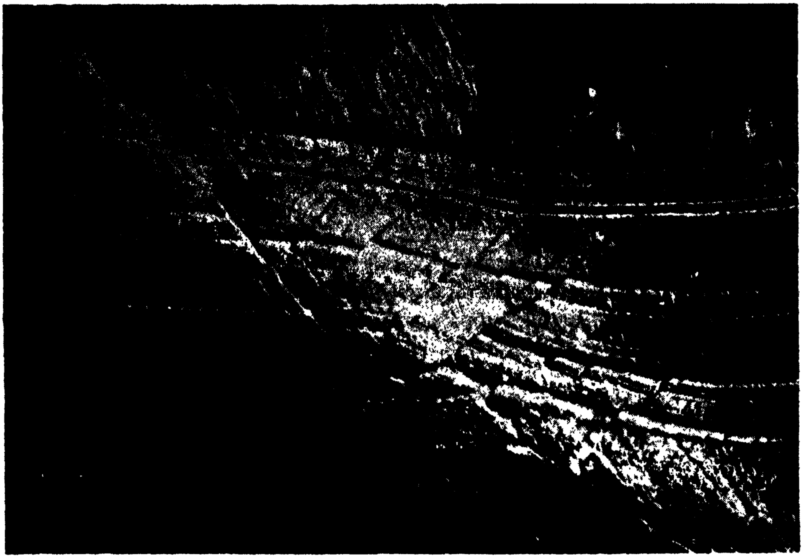


Fig. 86. Experimental reproduction of the structure shown in Fig. 85. Tension faulting produced in a laminated paste of wet clay by means of a movable support. (H. Cloos, 1931)

Even this seemingly uniform graben shows evidence of transverse elevations which divide it into basins. The stratigraphic development of the sediments north of the latitude of Karlsruhe is quite different from that south of it.[81] The line separating the two basins is an important seismic line, the "Kandeler Erdbebenlinie."[82]

Volcanic activity. As in the African rift valleys, volcanic rocks are scattered along the Rhine graben and its northern continuation in Hesse without any recognizable relation to the form or dimensions of the depression. The largest volcanic center, that of the Vogels-

[81] Walter H. Bucher, "Beitrag zur geologischen und palaeontologischen Kenntnis des jüngeren Tertiärs der Rheinpfalz," *Geognost. Jahreshefte,* Vol. 26, 1913, pp. 1-101, esp. p. 73.

[82] Carl Botzong, "Uber die Erdbeben Südwestdeutschlands, insbesondere über die der Rheinpfalz," *Pfaelzische Heimatkunde,* Vol. 8, 1912, pp. 41-5, 56-61.

berg, lies to the north, outside the sharply defined single fault trough. A smaller one, the Kaiserstuhl, is located in the southern part of the graben, not far from the center where the portion in which the pre-Tertiary rock of the region is faulted down out of sight is unusually narrow. Small masses of volcanics occur scattered along both sides of the graben, largely in the northern half.[83] Here as in East Africa from the Great Rift Valley to Abyssinia, the rocks belong to the alkaline series, with nephelite basalts, phonolites, etc.

3. Triassic Basins of Eastern United States

Observations in Pennsylvania. With this picture of the two standard examples of fracture belts of low mobility in mind, we may turn once more to American examples. The Triassic fault troughs of the Atlantic border, generally with a major fracture on one side and a flexure on the other, have suffered little folding since their formation. Yet even they show evidence of vertical upward movement of the marginal welts subsequent to the main phase of sinking, clearly associated with the general uplift which ended the geosynclinal tendency of that time. Stose's recent detailed description of the Upper Triassic sediments in the vicinity of Gettysburg may serve as illustration.[84] Deposition began with the formation of a furrow, the western border of which sooner or later assumed the character of a fault. But this fault did not find expression in the topography. It seems rather that the filling of the trough took place largely through the influx of sediment from the eastern border. "Sediments were deposited in a long, narrow basin that progressively deepened westward, the first deposits being laid down only in the eastern part of the basin and later deposits spreading progressively farther west. Only a small part of the total thickness of sediments should therefore be found at any one place." Stose computes the total thickness as about 23,000 feet. The closing stages of sedimentation, on the other hand, record uplift along the western edge, indicated by a line of coarse conglomerates which skirt the western border fault. They are typical fanglomerates. Their alignment, which Stose illustrates by a

[83] In the southern half, e.g., the basalt of Rappoltsweiler and Reichenweier west of the Kaiserstuhl and that of Reichshofen west of Pechelbronn, both on the west side of the valley.

[84] G. W. Stose and F. Bascom, "Fairfield-Gettysburg Folio, Pa.," *U.S. Geol. Survey, Folio 225,* 1929.

special map in the text (Fig. 7, p. 10), bears out this interpretation. "This material," in part composed of subangular fragments, "was deposited along the western border in huge alluvial fans at the mouths of mountain gorges and now forms a series of conical fanglomerate hills with escalloped edges along the mountain front."

Here, then, we recognize the same sequence of events we saw so clearly expressed physiographically and structurally in the rift valleys of the Rhine and of East Africa: First, a geosynclinal ("taphrogenic") phase followed by an orogenic phase which ended the downward movements in the trough as a whole and raised that side of the furrow into a welt along which the sediments had reached their greatest thickness. The surface trace of the western border fault is jagged and angular as in all such fractures of essentially tensional origin.

Stose's diagrammatic figures imply that the intrusion of the trap sill and accompanying dikes was contemporaneous with the orogenic phase. So far as the writer knows, this is a pure assumption and contrary to the experience in other regions. For the New Jersey and Connecticut traps Davis "called attention to the raggedness of some of the contacts [between intruded trap and sediments] as evidence that the intrusion was effected before the development of joints by the uplift of the formation."[85] In view of his own detailed studies of the traps in the New Jersey region, Darton considered this suggestion as "very probable." In the Connecticut Valley, the "peculiar sympathy in the order of arrangement between the eastern and western [trap] ridges" seem to prove conclusively "that the dikes and sills, as well as the sheets, were present before the formation was disturbed, and that all suffered tilting and faulting together."

Observations in Connecticut. The Triassic trough of the Connecticut Valley shows essentially the same sequence of events as that of the Gettysburg region. Close to the great eastern border fault, especially in the southern part, there lie very coarse fanglomerates. The variation of coarseness along the strike of the beds clearly shows where the

[85] N. H. Darton, "The Relations of the Traps of the Newark System in the New Jersey Region," *U.S. Geol. Survey, Bull. 67*, 1890, p. 73.

centers of the fans had been which mark the mouths of valleys from which the fans were built outward.[86]

Longwell emphasizes the fact that these coarse fan deposits appeared late in the period of sedimentation, after "sediments thousands of feet in thickness had already accumulated in the Triassic trough." In contrast to Davis' earlier view, Longwell finds that "there is good suggestive evidence . . . that recurrent faulting maintained the eastern border of the Triassic area near its present position during a considerable part of the period of sedimentation." But these fan deposits near the end of sedimentation in this southern part of the trough show that here, too, positive uplift, such as we associate with an orogenic epoch, ended the recorded part of the history of the region.

As in most other fractured regions of relatively low mobility, there is here also doubt as to the attitude of the border fault. Barrell seems to have contemplated the possibility that it might have the nature of a steep thrust, dipping eastward.[87] But the angular zigzag pattern, which we found so characteristic of tension fractures, is beautifully developed as may be seen from Davis' map.[88]

Discussions of the faulting of the interior of the Connecticut trough in many cases clearly are based on an inspection of cross-sections only, such as accompany Davis' classical report[89] or Barrell's much-quoted paper.[90] They are frequently spoken of as though they were longitudinal faults, essentially connected with the deformation of the trough as a whole. But the geological map shows that they are peculiarly localized oblique fractures. They bear the same relation to the eastern border fault which the oblique faults of the Coast Ranges of California bear to the master faults. They are "pinnate" fractures.

They obviously came into existence later than the lines of flexing or faulting which bound the basins themselves. As in the case of the Coast Ranges of California, the main faults and lines of flexing are

[86] See excellent description of these truly remarkable deposits in C. R. Longwell, "Notes on the Structure of the Triassic Rocks in Southern Connecticut," *Am. Jour. Sci.*, Vol. 4, 1922, pp. 231-6.

[87] C. R. Longwell, *op. cit.*, p. 230.

[88] W. M. Davis, "The Triassic Formation of Connecticut," *U.S. Geol. Survey, Eighteenth Ann. Report*, Vol. II, 1898, Pl. XIX (in pocket).

[89] *op. cit.*, on Pl. XX, in pocket.

[90] J. Barrell, "Central Connecticut in the Geologic Past," *Connecticut Geol. and Nat. Hist. Survey, Bull. 23*, 1915.

interpreted as the result of crustal tension. The oblique "barb" fractures, on the other hand, are thought to be shear fractures produced by slight rotational strain incident to the compression of the orogenic epoch which closed the depositional history of the Triassic trough. That these oblique fractures came into existence at the end of the sinking of the Connecticut trough was inferred by Barrell. He wrote: "The lack of any known sediments deposited in basins from the erosion of the fault blocks suggests that general uplift prevailed over the whole Appalachian province and that the differential movement between the blocks was one of different degrees of uplift; that there was nowhere real downsinking. The greatest erosion was on the two sides of the basins facing each other," separated by the arch located between the Connecticut and Hudson Rivers of today.

Barrell might well have stated more explicitly that the formation of the trough quite plainly was due to essentially the opposite process. The record of the "geosynclinal" or "taphrogenic" phase is one essentially of sinking and sedimentation with no tangible evidence of important orogenic phases. Throughout most of that time which, according to our view, was one of crustal tension, the eastern border of the Connecticut trough and the western border of that of New Jersey and Pennsylvania functioned as fault scarps. These master faults, then, exactly as in the Coast Ranges and elsewhere, are older than the "pinnate" fractures which later developed under the stresses of orogenic epochs. They came into existence as tension faults. In this respect, then, the deformational history of the Triassic troughs of the eastern United States agrees with other typical fracture belts.

Local folding. In the Triassic troughs of the eastern United States, as in other great regions of graben faulting, evidence of crustal compression is locally more pronounced.

In the Richmond basin, for instance, sharp folding and overthrusting occur locally.[91] Here, as in the Rhine graben and the African rift valleys, the evidence of compressive stresses was extrapolated far beyond the action indicated. Shaler and Woodworth wrote: "The

[91] A good thrust fault is described by Shaler and Woodworth from an exposure along the west side of the basin, southeast of Mosley Junction. See detailed section on Pl. XXXVIII, opp. p. 478, in N.S. Shaler and J. B. Woodworth, "Geology of the Richmond Basin, Virginia," *U.S. Geol. Survey, Nineteenth Ann. Report,* Part II, 1899. Sharp folding occurs also on the east side, in the outlying synclines southeast of Midlothian.

hypothesis of direct downfaulting, unassociated with horizontally acting compressive stress, such as is assumed by some writers in accounting for graben valleys, does not seem to be applicable in this area."[92] Here, then, we have in the discussions concerning the origin of the Triassic troughs the same conflict between an explanation through tension and one through compression. It is significant that no one has suggested the third possibility, that of deep-seated thrusting concealed by surficial gravity slumping. The region is too deeply eroded for such secrets to be hidden. One seems justified in concluding that, instead, it reveals the incorrectness of such an interpretation for the corresponding younger fault troughs of Africa and the Rhine Valley.

Transverse axes. In several of the Triassic troughs, tranverse elevations occur along which locally the outcropping formations strike at right angles to the axes of the troughs. Such is, for instance, the axis which, in the Connecticut Valley, brings to the surface the main trap sheets south of Hartford, in Cedar Mountain. A better example is the ridge of pre-Cambrian rocks which cuts in two the small Farmville basin of Virginia.[93] The abnormal strike of the beds in the Deep River coal field of North Carolina seems to be due to a similar condition, complicated by faulting.[94]

We have seen before that similar transverse axes are common to all grabens. They arose probably through differential vertical movements along the graben floor in the course of orogenic deformation. They will ultimately be understood only when they are viewed as features typically associated with rift valleys.

Minor differential vertical movements are indicated by the "half-boat" structure commonly shown by the sills and lava flows associated with the Triassic sediments.[95]

[92] *op. cit.*, p. 410.

[93] See map on Pl. III of J. K. Roberts, "The Geology of the Virginia Triassic," *Virginia Geol. Survey, Bull. 29*, 1928 (in pocket).

[94] See map in M. R. Campbell and K. W. Kimball, "The Deep River Coal Field of North Carolina," *North Carolina Geol. and Econ. Survey, Bull. 33*, 1923, pp. 61-4.

[95] See, e.g., the three shown on Davis' "Geological Map of the Triassic Area of Connecticut," *op. cit.*; the Gettysburg sill as shown on the sketch map, Fig. 8, p. 11, of G. W. Stose and F. Bascom in the "Fairfield-Gettysburg Folio," *Folio No. 225*, 1929; the curved bands of diabase on the map of the Potomac area obviously represent similar sills, although Roberts speaks of them as "dikes," "upwards of a mile in width at times." See J. K. Roberts, *op. cit.*, Pl. I (in pocket).

Volcanic activity. The similarity between the Triassic troughs and the best known younger fracture belts extends to the irregular distribution of volcanic activity. The great intrusive trap sheet and the lava flows of Connecticut are famous. It is less well known that here, exactly as along the Rhine graben and the East African fractures, volcanic outbreaks occurred also on the uplands adjoining the fault troughs. In the coarse fanglomerates along the eastern border of the trough pebbles and boulders of vesicular basalt are abundant. Since there is nowhere any evidence of erosional unconformities on the lava flows of the trough itself, they must have been derived from the upland to the east together with the other detritus. Basalt dikes cutting the crystalline rocks of the upland are not uncommon. They are all that is left now of the volcanic activity which was most likely contemporaneous with the flows in the lowland.[96]

In the Scottsville trough, J. K. Roberts affirms that the "trap" pebbles are not of Catoctin origin as in the trap conglomerates farther north, but were derived "from pre-Triassic diabase intrusives and some of them possibly from . . . early Triassic flows."[97] The suggestion that these "flows" were "early" Triassic is not founded on any evidence. They were more likely contemporaneous with the volcanic activity in the trough, as in other regions.

4. The Great Basin

Views of origin. All the features which we have recognized as typical in the great fracture belts described on the preceding pages are equally characteristic of the structure of the Great Basin insofar as this vast region can be treated as a unit at all. This is in a way evident from the nature of the hypotheses that have been advanced to explain it.

In the early 'seventies, the fundamental feature of Great Basin structure was clearly recognized. Gilbert, with his eye directed to the surface expression of the region, emphasized the point that the forces concerned in the upheaval of the Basin Ranges, "whatever may have been their ultimate sources and directions . . . have manifested themselves at the surface as simple agents of uplift, acting in

[96] C. R. Longwell, "Notes on the Structure of the Triassic Rocks in Southern Connecticut," *Am. Jour. Sci.*, Vol. 4, 1922, pp. 234-5.

[97] *op. cit.*, pp. 19-22.

vertical or nearly vertical planes. . . ."[98] Four years later, King wrote more specifically: "The geological province of the Great Basin, therefore, is one which has suffered two different types of dynamic action; one, in which the chief factor evidently was tangential compression, which resulted in contraction and plication, presumably in post-Jurassic time; the other strictly vertical action, presumably within the Tertiary, in which there are few evidences or traces of tangential compression."[99]

In the same year, 1878, LeConte published a paper in which he "tried to show that even the Basin ranges—claimed by Gilbert as belonging to a different type and formed in a different way—were . . . formed by lateral pressure; only that in this case the crust of the earth being rigid would not yield by mashing, but only by arching—the blocks of the broken arch readjusting themselves to form the orographic features . . . described."[100] Here we have deBeaumont's and Gregory's keystone hypothesis.

A decade later, LeConte adopted a radically different view. He wrote: "It is evident from the *character of the faults*, i.e., normal instead of reverse faults, that the arch was not formed by lateral *pressure* but by *tension of lifting*." He thought that the earth-crust was "*uplifted into an arch* by intumescence of the subcrust liquid. . . . Such an arch being put upon a stretch would be broken by long fissures more or less parallel to one another and to the axis of uplift. . . . After the outpouring of liquid lava or the escape of elastic vapors had relieved the tension, these crust blocks would again be readjusted by gravity."[101] Here we have the tensional hypothesis in one of its forms.

Most recently, the Andreae-Wayland hypothesis of thrust faults hidden at the surface by rectilinear landslide blocks was suggested as "*possibly* applicable to some basin range structures" by Link and

[98] G. K. Gilbert, *U.S. Geog. and Geol. Surveys, W. 100th Mer., Progress Report for 1872*, 1874, p. 50.

[99] Clarence King, *U.S. Geol. Expl., 40th Parallel*, Vol. I, 1878, p. 744.

[100] J. LeConte, "On the Structure and Origin of Mountains . . . ," *Am. Jour. Sci.*, 3rd ser., Vol. 16, 1878, pp. 95-112. This statement quoted from the next paper here referred to, p. 263.

[101] *idem*, "On the Origin of Normal Faults and of the Structure of the Basin Region," *Am. Jour. Sci.*, Vol. 38, 1889, pp. 259, 263.

illustrated by a diagram.[102] This completes the list of the three types of explanation which have been brought forth to account for the Rhine graben and the rift valleys of East Africa.

Structural and physiographic characteristics. All the properties that were recognized as characteristic for these two regions are present throughout the Great Basin, such as the zigzag character of the major faults; the transverse structures dividing even single grabens into several basins; the lack of correspondence between the character and degree of deformation and the intensity of volcanic action, etc. The Great Basin region as a whole shares with the others the elementary property of having the shape of a belt, being a number of times as long as wide.

Exactly as in the other regions, the idea that the mountains are merely inert blocks cut out of the surface by faulting, tilted, and left standing high ("horsts" in Suess' original sense), is proving increasingly inadequate. Warping and flexing of the surface of the "blocks" is being recognized physiographically just as detailed mapping proved the high masses of the Black Forest and Vosges Mountains to be far from rigid "horsts."

The writer is convinced that one element in the ultimate solution of the physiographic problems of the Great Basin will be the recognition of the different origin of the major fault pattern on the one hand and of the topographic ridges on the other. If the ridges are welts, formed under orogenic stresses on a surface previously broken by numerous tension faults, then the raising of individual welts need not be bound to fracture lines. The checkerboard pattern of faults would account for the discontinuous and seemingly haphazard distribution of the welts. But the rise of any specific welt would be determined by the complicated interplay of stresses within the heterogeneous outermost few miles of the crust's thickness. The upwarping may well affect parts of two adjoining fault blocks or only a portion of one. There need not be everywhere normal faults to mark the base of each "block mountain."

The geologist who wishes to understand the physiographic expression of the latest orogeny in the Great Basin should study first the physiography of the Coast Ranges. The idea that the structural and

[102] Theo. A. Link, "Relationship between Over- and Underthrusting as Revealed by Experiments," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 12, 1928, p. 851.

therefore physiographic character of the Great Basin was essentially the same as that of the Coast Ranges, the writer owes to Dr. Clark. He was driven to that view by the studies referred to in greater detail at the beginning of this chapter. A similar opinion was recently expressed in print by Bailey Willis and, in consequence of his recent visit to California, by Cloos. In both regions an interplay of tensional and compressional forces can alone explain the complicated structure and physiography. There is obviously a wide range of "mobility" in the Great Basin. Parts may be called "heterogeneous mobile belts," while others are "fracture belts of low mobility." The writer's knowledge of detail within this vast region is at present too limited to give him confidence in the selection of typical areas for detailed analysis. He must be content, then, with these few broad suggestions.

5. Résumé

We may summarize the results of the preceding discussions in one law and two formal "opinions":

Law 36 a. Among mobile belts, three types may be distinguished, as defined in the text: "homogeneous mobile belts"; "heterogeneous mobile belts"; "fracture belts of low mobility."

Law 36 b. These types grade into each other.

Opinion 27. The three types of mobile belts differ primarily in the manner in which the crust yielded under tensional stress, with much fracturing and normal faulting or with little or none.

Opinion 28. Differences in the distribution and rate of application of the stresses probably account for the different behavior of the crust within these belts rather than differences in the physical properties of the materials of which they are made.

CHAPTER XI

SPACE RELATIONS OF MOBILE BELTS

"... le besoin de changer et celui de rester immuable,
ces deux instincts passionnés de toute forte vie...."
Romain Rolland, in *L'âme enchantée.*

1. Intersection of Successive Mobile Belts

One significant property which was mentioned only casually in the preceding discussion of fracture belts of low mobility deserves more careful consideration. It is the divergence of the outlines of fault troughs from the lines of preexisting structures.

Rift valleys of East Africa. Over long distances, the rift valleys of East Africa cut across the trend of the much earlier, largely pre-Cambrian, structures. We have quoted already Gregory's phrase of fractures "breaking across the grain of the country." This is particularly conspicuous in Tanganyika Territory, the former German East Africa, where a repeated deflection to the southwest is a characteristic feature of the rift valley. "This southwestward deflection is doubtless due to the valley crossing the belt of Africa where the dominant geographical lines are diagonal. The major set of diagonal lines runs from northeast to southwest; they are dominant in the band bounded to the northwest by the line along the southern coast of Arabia, the Albert Nyanza, and the rift valleys of the eastern Congo, and to the southeast by the tectonic lines in Madagascar and South Africa, where a comparatively young fault has cut off the southeastern corner of the continent. The rift valley in central German East Africa traverses the middle of this band and shows its influence in the repeated deflection southwestward."[1]

Out of the multitude of local variations in the strike of the pre-Cambrian folds on the African continent, it seems that lines directed northwestward and northeastward, respectively, stand out as the dominant structural directions and not lines of meridional trend.[2]

[1] J. W. Gregory, *The Rift Valleys and Geology of East Africa,* London, 1921, p. 21.

[2] R. Ruedemann, "The Existence and Configuration of Pre-Cambrian Continents," *New York State Mus., Bull. 239-40,* 1922, p. 83.

Krenkel states this emphatically, and the material he has collected in the two volumes of his excellent *Geologie Afrikas* bear out this conclusion.[3] The north-south direction of the fracture belt cuts across these earlier structures.

Rhine graben. The Rhine graben, with its north-northeast strike, cuts similarly across the Variscan (northeast) strike of the late Paleozoic folds. This is well shown by any geological map of Europe. It is brought out most clearly on Reis' tectonic map to which reference has been made (p. 336).

Great Basin. In and along the Great Basin the truncation of the older structures by the outlines of the present orogenic units was recognized by Gilbert[4] as one of the characteristic features of the region. Davis focused attention on this property and illustrated it by a useful diagram.[5] One classical locality may serve to illustrate it. Speaking of the west front of the Wasatch Range in Utah, in his posthumously published paper, "Studies of Basin-Range Structure," Gilbert describes in detail the way "the range front transects the range structure." At a few places, "the strike of the strata is approximately parallel to the rock base," that is, to the line along which the waste of the desert plains meets the bed rock at the foot of the range. "But these localities are exceptional. Elsewhere, including not less than seven-eighths of the range front, the strike meets the rock base at a notable angle. The greatest fold of the range, a syncline that brings a great series of Paleozoic and Mesozoic formations in succession to the rock base, runs athwart the range in the latitude of Salt Lake City."[6] This relation is strikingly shown in a "diagrammatic geologic structure section and profile" of the west front of the Wasatch

[3] E. Krenkel, *Geologie Afrikas*, Berlin (Gebr. Borntraeger), 1925 (Vol. I), 1928 (Vol. II). See, e.g., Vol. I, pp. 25, 26, and 36.

[4] G. K. Gilbert, "Report on the Geology of Portions of Nevada, Utah, California, and Arizona, Examined in the Years 1871 and 1872," *U.S. Geog. and Geol. Surveys, W. 100th Mer. Rept.*, Vol. 3, 1875, p. 41 ("ridge lines are more persistent than structures").

[5] W. M. Davis, *Science*, N.W., Vol. 14, 1901, pp. 457-8. The diagram was reproduced in W. M. Davis, "The Wasatch, Canyon, and House Ranges, Utah," *Bull. Mus. Comp. Zool. Harvard*, Vol. 49 (Vol. 8, No. 2, of Geological Series), 1905, p. 24, Fig. 8.

[6] G. K. Gilbert, "Studies in Basin-Range Structure," *U.S. Geol. Survey, Prof. Paper 153*, 1928, p. 41. See esp. also the photographs referred to in the text on p. 41.

Mountains near Salt Lake City which was published by Schneider.[7] This diagram is, at the same time, a cross-section of the structure and a front view of the range.

Bartlett trough. Taber has shown recently[8] that the south face of the east-west striking Sierra Maestra of Cuba exhibits the same condition. The average strike within the belt of ranges which bears this name, is N 70° W, that is, approximately parallel to the main axis of Cuba. When this direction is added to Woodring's map, Fig. 2 (opposite p. 12), it is seen that the same strike dominates the structure of the islands east and south of the Bartlett trough. It is the trend of the ranges that parallel the northeast and southwest shores of Jamaica. Folds of the same trend strike obliquely across the southern peninsula of Haiti and constitute also the Cordillera de Cibao which forms the long axis of the main body of the island of Haiti. The Bartlett trough cuts thus sharply across the older axes of folding.

Triassic basins of Atlantic border. Main axes. A similar relation exists between the Triassic basins of our Atlantic border and the Appalachian folds. Here, however, it is not so generally recognized. The trend of the chain of Triassic basins from the northern border of South Carolina to Nova Scotia is obviously closely related to that of the earlier folds. Even on a large scale, when seen in the field, individual faults of Triassic age show a distinct dependence on Paleozoic structure lines. The result has been a tendency to think of the formation of the Triassic troughs and their subsequent warping as a sort of belated continuation of Paleozoic orogeny. If such a simple relation existed, one should expect that the main structural lines would have continued to function in the later deformation, or if not, that the new troughs would bear a reasonably uniform relation to the older structural axes. When Emerson suggests that "the outlines of the Connecticut Basin were determined in the Devonian period,"[9] he expresses the kind of relation one has in mind.

But the geologic map of the eastern United States shows quite a different picture. On an earlier page (pp. 174-81) attention was called

[7] Hyrum Schneider, "A Discussion of Certain Geologic Features of the Wasatch Mountains," *Jour. Geol.*, Vol. 33, 1925, p. 33, Fig. 3.

[8] Stephen Taber, paper given before Geological Society of America, 1932, to be published in *Bulletin*.

[9] B. K. Emerson, "Geology of Massachusetts and Rhode Island," *U.S. Geol. Survey, Bull. 597*, 1917, p. 127.

to the three large units that dominate the crystalline Appalachians from Virginia to Pennsylvania: the Martic thrust block, the synclinal belt of Paleozoic limestones, and the Blue Ridge welt. Of these, the synclinal limestone belt, which runs from the vicinity of Charlottesville, Va., to the Chester Valley north of Philadelphia, offers a convenient line of reference. Compare with it the trend of the Triassic troughs. The southernmost of the western chain of troughs, the Dan River, Danville, and Farmville basins lie well to the east of the synclinal belt,[10] the latter about 25 miles east of it. Their distance from the western border of the crystalline axis of the Blue Ridge welt amounts to about 50 miles. Some 300 miles farther north, on the other hand, south of Harrisburg, Pa., we find the Triassic area lying well to the west of the synclinal limestone belt, extending even across the Blue Ridge axis to meet the limestones of the Appalachian Valley. Between these two extremes, therefore, the line of Triassic troughs cuts across the main axes of the preexisting Paleozoic structure as definitely as in the other regions quoted, although, at a more acute angle. The formation of the Triassic troughs must represent a new start dynamically which disrupted the old structural lines.

Trap dikes. The discordant relation between the major axes of the Paleozoic folding and the fracture lines associated with the formation of the Triassic basins is demonstrated neatly by the long trap dikes that cut across the older structures outside the areas occupied by Triassic sediments. In Pennsylvania, the great Bellevue-Georgetown-Centerville dike runs in a north-northeast-south-southwest direction for a distance of over 22 miles across Lancaster County, "leading in a well defined line through the older rocks," as Frazer put it in 1880.[11] The geologic state map shows well the way the dike cuts across the boundary lines of the pre-Cambrian metamorphics and especially across the narrow synclinal band of Cambro-Ordovician limestones of the Quarryville valley.

The geologic map of Maryland[12] shows another such major dike outside the Triassic areas, which can be traced again in a north-

[10] See G. W. Stose, *Geologic Map of Virginia,* 1:500,000, Virginia Geol. Survey.

[11] P. Frazer, "The Geology of Lancaster County," *2nd Geol. Sur. Pennsylvania, Report CCC,* 1880, p. 2. See esp. map in pocket. See also *Geologic Map of Pennsylvania,* by A. D. W. Smith, under the direction of J. P. Lesley, 1893.

[12] *Map of Maryland Showing the Geological Formations . . . ,*" Maryland Geol. Survey, 1907.

northeast direction, essentially as a unit, with only minor interruptions, for a distance of over 45 miles. According to the map, it begins southwest of Clarksville and reaches the Pennsylvania border just east of the Harford-Baltimore County line. The geologic map shows convincingly that the trend of this major structural line is wholly independent of the earlier folding.

It is typical of the undeveloped state of our knowledge of the eastern Appalachian region that no comprehensive study of these really remarkable dike systems has been published. The first line of dikes, in Howard and Baltimore Counties, for instance, ends abruptly at the state line on the geologic map. The geologic map of York County just across the border in Pennsylvania, shows no signs of it. The large number of dikes in places, and the ease with which the basic rock of the dikes decomposes making exposures scarce over long stretches, renders a systematic tracing of these dikes difficult. One such attempt was made by Lewis. He traced a line of trap dikes across southeastern Pennsylvania, "from near Doylestown to Maryland . . . which, taken together with some parallel dykes of similar nature and composition north and east of Doylestown, forms a series of nearly continuous dykes some ninety miles in length."[13]

In places this dike reaches a width of a hundred feet. It towers in a conspicuous outcrop above the road on the edge of the town of West Conshohocken. This part of the dike was described as early as 1858 by H. D. Rogers in his report on the geology of Pennsylvania.

Lewis did not follow this chain of dikes into Maryland. There it is probably continued in the "series of dikes" which "enters Cecil County from Pennsylvania and extends into Harford County."[14]

This easternmost chain of dikes seems to conform more nearly to the strike of the pre-Cambrian folds than any of the great dikes mentioned above. On the other side of the Triassic belt, however, where south of Harrisburg the Triassic sediments touch the folds of the Appalachian Valley, a belt of "trap" dikes strikes out in a northerly direction, cutting straight across the western end of the most famous

[13] H. C. Lewis, "A Great Trap Dyke across Southeastern Pennsylvania," *Proc. Am. Philos. Soc.*, Vol. 22, 1885, pp. 438-56. See esp. topographic map 1:300,000 accompanying the paper, on which the dike is represented by a red line.

[14] W. B. Clark and E. B. Mathews, "The Physical Features of Maryland," *Maryland Geol. Survey*, Vol. 6, 1906, p. 118.

of the zigzag folds of Pennsylvania.[15] The southern part of this belt is a single dike which arises in the South Mountain and cuts across the Cumberland Valley in Cumberland County, where it is "so conspicuous a landmark that it has been adopted as the boundary line between four townships."[16] In its northern continuation, in Perry County, it is replaced by several more or less parallel dikes that extend across the Juniata River.

There can be no doubt that these remarkable belts of dikes represent major lines of fracture. They are discontinuous partly because the fracture itself was discontinuous, at least at the surface. We are apt to lose sight of the fact that such disjunctive fractures, opening up from below, and with them the volcanic materials that rise along them, need never reach the surface. Many certainly do not.

The famous Cleveland dike of northern England[17] with a known length of at least 110 miles crops out at the surface intermittently. Its continuity over the whole distance is proven by quarry and colliery workings.[18] In the case of the last named of the trap dikes of Pennsylvania, in Perry County, there exists likewise good field evidence that some of the dikes did not reach to the surface[19] at an earlier stage of erosion, being continuous at greater depth and lying now exposed.

It is to be hoped that these remarkable trap dikes of our eastern States will receive the monographic study they deserve.

All the examples given so far represent fracture zones of low mobility cutting across older folds. Most geologists associate the concept of tensional stresses with "normal" fractures. There is, there-

[15] See *Geologic Map of Pennsylvania.*

[16] E. W. Claypole, "A Preliminary Report on the Paleontology of Perry County . . . ," *2nd Geol. Sur. Pennsylvania, Rept. of Progress F2,* 1885, p. 295.

[17] J. J. H. Teall, "Petrological Notes on Some North-of-England Dykes," *Quart. Jour. Geol. Soc.,* Vol. 40, 1884, pp. 209-46. Teall's figure of this exposure is reproduced in E. Suess, *The Face of the Earth* (trans. by Sollas and Sollas), Vol. IV, p. 572, Fig. 51.

For a reproduction from Geikie of longitudinal sections of the dike, showing its intermittent outcrop, see R. A. Daly, *Igneous Rocks and Their Origin,* New York, 1914, p. 182.

[18] In a quarry near Cockfield the "vertical dying-out of the dyke beneath the stratified rocks" was exposed to full view. See A. Geikie, *Ancient Volcanoes of Great Britain,* London, Vol. II, 1897, p. 143.

[19] E. W. Claypole, *op. cit.,* p. 299. For another example of North American dikes known only from underground workings, see p. 357.

fore, nothing particularly surprising in the fact that such fracture belts intersect older structural lines. Exactly the same relation prevails, however, where the folds of a later mobile belt meet those of an earlier one. This fact is little recognized in America, because it is not as obvious here as in Europe.

Appalachian folds east of the Adirondacks. Let us examine American examples first. In the eastern United States, the folds of the Paleozoic Appalachians meet those of pre-Cambrian orogeny on the east side of the Adirondacks. Recently Buddington has assembled what is known about the position of the axes of pre-Cambrian folding in the Adirondacks. The reader will do well to turn to this map which shows the "generalized trends of foliation in the Adirondacks."[20]

Sufficient data are available only south of the central Anorthosite body. Here the northeasterly strike which prevails further west appears deflected into an easterly direction. As far as data are available, the average strike of the pre-Cambrian folds is more or less east-west from Ticonderoga to Saratoga Springs. The contrast with the north-south strike of the Appalachian folds east of the Hudson River is as great as it could be. Here the furrow of the early Paleozoic geosyncline cuts across the old folds practically at a right angle, certainly in as striking a fashion as any of the fracture belts quoted above.

Mississippi embayment. East of the Adirondacks, the early Paleozoic furrow cuts across the much older structures much as the "Mississippi embayment" transects the late Paleozoic folds of the Ouachita Mountains in Arkansas. This comparison deserves a short digression. The new geologic map of Arkansas[21] shows beautifully how the western edge of the embayment terminates the folds abruptly.

For a distance of about three hundred miles, from southwestern Arkansas to southern Illinois, the edge of this trough borders the Paleozoic rocks exposed on the present surface. For that distance, it corresponds distinctly to what we may expect an incipient geosyncline to look like. The geologic map of North America shows the curious asymmetry of the rocks in the embayment as it appears today.

[20] A. F. Buddington, "Granite Phacoliths and Their Contact Zones in the Northwest Adirondacks," *N.Y. State Mus., Bull. 281,* 1929, Fig. 44 (scale approx. 1:500,000).

[21] *Geologic Map of Arkansas,* 1:500,000, Arkansas Geol. Survey, 1929.

The remarkably straight western border, where practically no Cretaceous sediments are visible at the surface, seems to represent a relatively sharp flexure, with faults farther out under cover.

Special interest attaches to the northern ending of this trough. To see it adequately, the reader should use Jillson's new geologic map of Kentucky.[22] Here, at the northern end of the embayment, a large number of faults emerges from beneath the Tertiary cover. They form a belt nearly fifty miles wide[23] from the fault zone that crosses the Ohio River at Shawneetown, Gallatin County, Ill., to that which traverses the Cumberland River in the vicinity of Eddyville, Lyon County, Ky. The geologic map shows well how the strike of the dominant faults in this belt swings from northeast through east-northeast into an easterly trend and even somewhat south of east. At a distance of forty miles from the northern end of the embayment most of the faults have played out. Only the two major fault belts continue eastward with interruptions, and more or less *en échelon.* The northern belt is continued east of Shawneetown in the faults roughly located by the towns Sebree, Livermore, Sulphur Springs, Leitchfield, Grayson Springs. The southern belt has been traced eastward from Eddyville to within a few miles of Morgantown on Green River.

These two fault belts converge toward the country north of Green River, near Mammoth Cave. Here, in a narrow zone, hardly more than three miles wide, Pottsville sandstone is preserved in a chain of outliers extending for about 35 miles eastward from the eastern edge of the western coal fields of Kentucky.[24] Locally this zone is bounded by faults.

Twenty miles east of the easternmost Pottsville outlier of this zone another fault belt begins which has been traced almost continuously for a distance of about 120 miles, from east of Lebanon in Marion County, to north of Paintsville, in Johnson County. There is an offset

[22] W. R. Jillson, *Geologic Map of Kentucky,* 1:500,000, Kentucky Geol. Survey, 1929.

[23] For a good illustration of the details of this zone see the "outline map showing faults" and the structure section on Fig. 12, opp. p. 100, in Stuart Weller, "Geology of the Princeton, Ky., Quadrangle," *Kentucky Geol. Survey,* 6th ser., Vol. 10, 1923.

[24] W. G. Burroughs, "A Pottsville-filled Channel in the Mississippian," *Kentucky Geol. Survey,* 6th ser., Vol. 10, 1923, pp. 115-26. The map which accompanies this paper shows a greater extent of Pottsville sediments than the new edition of the state map.

in this belt near Stanford, in Lincoln County, where the Kentucky River fault zone branches off, which can be traced continuously for a distance of 100 miles to the vicinity of Maysville on the Ohio River.

While the vertical displacement is nowhere great, this system of faulting achieves significance by its extent. It is clearly primarily a system of tension fractures. It springs from the upper end of the Mississippian embayment.

To the writer it seems possible that this east-west system of tension fractures is due to the same weak tensional strain to which the Tertiary phase, at least, of the Mississippi embayment owes its origin. If this is correct, the fault zone marks the direction in which the pulling apart of the crust and with it the formation of the furrow would have proceeded eastward, giving rise to an arcuate geosyncline, if tension had been carried farther. This geosyncline would have cut across the Paleozoic folds in Arkansas and might have paralleled them in West Virginia and Pennsylvania.[25] Later crustal compression might have thrown the Cretaceous and Tertiary sediments into folds giving rise to a new mountain system.

Even if this flight of imagination has the right direction, what we actually see represents at best an abortive attempt at the making of a geosynclinal furrow. The actual movement has everywhere been trifling. There is little evidence of deep sinking in the northern part of the embayment, at least.[26]

The rise of basic magma, which so frequently accompanies the formation of a geosyncline, has similarly taken place on but a diminutive scale. Yet it is worth while to point out that peridotite dikes seem to be grouped in unusual numbers around the northern end of the Mississippi embayment. The geological map of Kentucky shows sixteen dikes in Crittenden and Caldwell Counties, Ky., and Pope

[25] See J. H. Gardner, "A Stratigraphic Disturbance through the Ohio Valley, Running from the Appalachian Plateau in Pennsylvania to the Ozark Mountains in Missouri," *Bull. Geol. Soc. America*, Vol. 26, 1915, pp. 477-83.

[26] See, e.g., the more or less hypothetical section in A. H. Purdue, "Water Resources of the Contact Region between the Paleozoic and Mississippi Embayment Deposits in Northern Arkansas," *U.S. Geol. Survey, Water-Supply Paper 145*, 1905, pp. 88-119; esp. Fig. 28, p. 103.

and Hardin Counties, Ill. On the Illinois side, the Sparks Hill volcanic neck even contains tuffs.[27]

In Sabine County, Ill., in the Harrisburg region from Eldorado south to Carriers Mills, a number of peridotitic dikes were encountered in mines, where they cut coal No. 5. Cady has given us details concerning ten of these dikes.[28] One has been traced over a distance of one and one-half miles. While most are thin, from two to fifty feet wide, one was found three hundred feet wide which had silicified the coal for a distance of twenty feet and coked it beyond. No outcrops of dike rock are known in this county nor has it been identified in the numerous drill cores from this region. This shows that here as elsewhere greater significance attaches to the scattered outcrops of basic dikes than their diminutive size and small number seem to warrant.

Across the Mississippi River, in Ste. Genevieve County, Mo., three peridotite dikes appear at the surface, all within one to three miles of Avon, near the southern border of the county.[29] We may note in passing that another zone of faulting radiates from the northern end of the embayment. It runs from Union County, Ill., crosses the Mississippi at Wittenberg and continues through Perry County,[30] Mo., into Ste. Genevieve County, Mo., where Weller's map gives a beautiful picture of its details.

The material of the peridotitic dikes around the northern end of the embayment is entirely similar to that which fills the dikes and volcanic necks at the southwestern end of the embayment in Arkansas. Here, in southern Arkansas, scattered basic dikes occur from the edge of the Tertiary east of Hot Springs to within thirty miles of the Oklahoma line. The diamond-bearing volcanic necks a few miles southeast of Murfreesboro, in Pike County, extend upward through beds of the Lower Cretaceous (Trinity), while water-laid perido-

[27] L. W. Currier, in Stuart Weller, "The Geology of Hardin County," *Illinois Geol. Survey*, Vol. 41, 1920, pp. 237-44. Also the geologic map accompanying this report.

[28] G. H. Cady, "Coal Resources of District V (Sabine and Gallatin Counties)," *Illinois Geol. Survey, Cooperative Mining Series, Bull. 19*, 1919, pp. 34-5, 56-61; see esp. Table 7, p. 60, and map, Pl. 1, in pocket.

[29] Stuart Weller, "Geology of Ste. Genevieve County, Mo.," *Missouri Geol. Survey*, 2nd ser., Vol. 22, 1928, p. 249, and esp. geologic map in pocket.

[30] R. F. Flint, "Thrust Faults in Southeastern Missouri," *Am. Jour. Sci.*, 5th ser., Vol. 12, 1926, pp. 37-40.

titic material occurs in the lower part of the Upper Cretaceous Tokio formation. Here, then, it is certain that the volcanic activity accompanied the downwarping that initiated the formation of the transverse embayment. It seems probable that the similar igneous rocks at the northern end of the embayment were intruded at about the same time.[31]

The sub-Betic geosyncline of Spain. The areal relations of the embryonic Tertiary Mississippi geosyncline to the Ouachita Mountain folds is duplicated in an instructive manner in southern Spain by that of the Andalusian lowland to the Sierra Morena. The reader should consult the international geological map of Europe for an impressive picture of this region.[32] The name Sierra Morena is applied to the southern border of the Spanish Meseta which rises above the lowland of Guadalquivir River. Any good topographic map of Spain shows that there is no mountain range corresponding to that name. The upland to which the name applies consists rather of a series of ridges which trend in a northwest-southeast direction. They terminate abruptly at the east-west escarpment which is skirted for a long distance by the Guadalquivir. The folds of the Sierra Morena upland are thus a counterpart to those of the Ouachita Mountains and the Guadalquivir "fault" line corresponds to the straight west border of the Mississippi embayment. But the lowland of Andalusia, with its Tertiary and Cretaceous sediments, is but the western part of a much greater geosyncline, the sub-Betic geosyncline which has been folded intensely, with large low-angle faulting and, according to Staub, with *decken* of Western Alpine type, pushed northward, of truly Alpine dimensions.[33] Here we have a homogeneous mobile belt of Mesozoic-Tertiary age cutting across the folds of an older mobile belt of late Paleozoic age at an angle of about 45°.

The sub-Alpine geosyncline of the Dauphiné. The intersection described above is as sharp and striking as any we find in the fracture

[31] C. S. Ross, H. D. Miser, and L. W. Stephenson, "Water-laid Volcanic Rocks of Early Upper Cretaceous Age in Southwestern Arkansas, Southeastern Oklahoma and Northeastern Texas," *U.S. Geol. Survey, Prof. Paper 154-F,* 1929, pp. 175-202, esp. p. 193.

[32] *Carte géologique internationale de l'Europe,* 1:1,500,000; sheets 29 (A V), 30 (B V), 36 (A VI), and 37 (B VI).

[33] R. Staub, "Gedanken zur Tektonik Spaniens," *Vierteljahrsschrift der Naturf. Ges. Zürich,* 1926; also translated, "Ideas sobre la tectonica de España," *Real Acad. Sci.,* Cordoba, 1927.

belts of low mobility. But while it is conspicuous, it is by no means exceptional. Six hundred miles to the northeast, along the eastern border of the Plateau Central of France, we find this same relation. Here, on the west side of the Rhone River, between Valence and Lyon, we see the axes of the Paleozoic folds which trend southwest-northeast, cut off abruptly by the north-south-trending western border of the lowland of the Lower Dauphiné.[84] This represents the latest westward extension of the Alpine geosyncline. The marginal folds of the West-Alpine arc, some thirty to fifty miles to the east, show an average north-south trend, obviously independent of the strike of the earlier orogenic unit.

The Flysch zone of the Carpathians. Another six hundred miles in an east-northeast direction, south of the Sudetes, the folds of the late Paleozoic geosyncline are overridden by those of the Cretaceous Tertiary geosyncline of the Carpathians. Here, between Brünn and Troppau, Devonian and Mississippian sediments lie thrown into steep folds which trend approximately in a north-south direction. They are overwhelmed by the thrust sheets (*decken*) of the Flysch zone of the Carpathians which strike in a northeasterly direction.[85] The broader folds of the Pennsylvanian coal region of Ostrau and Karwin have been proved by drilling to extend far beneath the Tertiary thrust sheets.[86] Here again the late Paleozoic and the Tertiary geosynclines intersect at an angle of about 45°.

"Hercynian" versus "Alpine" geosynclines. The full significance of these cases in which the "Hercynian" and the "Alpine" geosynclines intersect becomes evident only when the two systems are compared in their entirety. In Fig. 87 Staub's attempt to reconstruct the late

[84] See sheets 30 (B V) and 31 (C V) of the *Carte géologique internationale de l'Europe.* Also Pl. VIII (in pocket) of L. de Launay, *Géologie de la France,* Paris, 1921.

[85] This is well shown on von Bubnoff's "Geologische Strukturkarte von Mitteleuropa" (approx. 1:2,500,000) in Wilh. Salomon, *Grundzüge der Geologie,* Vol. I, 1924, Pl. I. This may be supplemented by V. Uhlig's tectonic sketch map of the Carpathians reproduced in the French edition of Suess' *The Face of the Earth,* Vol. III, Part 2, p. 857 (original in *Sitz. Ber. Kgl. Akad. Wiss. Wien, Math.-nat. Kl.,* Vol. 116, Abt. 1, 1907, p. 982).

[86] For an instructive picture of this relation see Map 44 of the atlas accompanying the *Coal Resources of the World,* edited by W. McInnes, D. B. Dowling, and W. W. Leach and issued by the 12th International Geological Congress, Toronto, 1913.

Fig. 87. The late Paleozoic ("Hercynian") mobile belt of Europe.
Vertical ruling = foreland; diagonal ruling = hinterland. White = Hercynian mobile belt; black (*G*) = "Zwischengebirge"; *A* = Armorican arc; *V* = Variscan arc.

(R. Staub, 1928; reproduced from *Der Bewegungsmechanismus der Erde*, by permission of Verlagsbuchhandlung Gebrüder Borntraeger)

Paleozoic system of geosynclines is reproduced.[37] This should be studied carefully by comparison with a good geologic map of Europe, preferably the *International Geologic Map* (1 :1,500,000). It will be seen at once that the complicated crustal movements of late Tertiary and Pleistocene time have covered large sections of this great system of geosynclines with sediments or with water. The diagram connects the visible fragments by continuous lines which are, of course, highly generalized. The main geosynclines are represented by the white bands, with heavy black lines marking the chief axes of folding. The foreland, toward which the main folding is directed, is marked by vertical ruling, the hinterland by oblique ruling. The black area marked "G" is interpreted as "Zwischengebirge."[38] The heavy dashed lines in the foreland represent lines of folding which are interpreted

[37] Reproduced from R. Staub, *Der Bewegungsmechanismus der Erde*, Berlin, 1928, Fig. 34, p. 186.
[38] See p. 81.

by Staub as offshoots from the main orogenic axis. The black lines and those marked by dashes and dots in the hinterland mark structural axes. For their interpretation, the reader is referred to the original.

We are here concerned only with the main geosynclinal axes. The conspicuous loop at the southwest end of the system is well attested by large fragments lying between the Sierra Morena in the southwest and the famous folded Paleozoic formations of Asturias. Suess has given an excellent description[39] of the right-angle bend of the orogenic axis in the northwest of the peninsula. The map reproduces and, better still, the *International Geologic Map*[40] shows well how the strike of the folds swings from an east-southeast direction in the Montanas de Leon into the north-northeast direction of the Sierras west of Ovideo which strike the shore of the Bay of Biscay nearly at right angles.

In some way this broad belt of Paleozoic folds must have joined that which runs out into the sea in Brittany and Cornwall. The connecting portion must lie hidden beneath the Bay of Biscay. Whatever its form may have been in detail, it constituted probably an arc such as appears in Staub's diagram, labelled *A* ("Armorican arc"). The great geosynclinal belt which runs first southeast, then northeast through northern Europe is well known and so is the great arc which curves about Bohemia on three sides. It is marked *V* ("Variscan arc") on Staub's diagram. The southern limb of this arc, which trends south-southwest, forms the folds south of the Sudetes which were mentioned above. Their continuation lies buried beneath the thrust sheets of the Carpathians and the late Tertiary basin of Vienna. But farther south, in Styria, at the eastern end of the Alps, especially in the vicinity of Graz, the Paleozoic geosynclinal sediments appear again at the surface with a northeast strike. The thick Devonian sediments of this region resemble those of the Sudetes so closely that as much as sixty years ago Stur concluded that they must have been deposited in a sedimentary basin which was in direct connection with

[39] E. Suess, *The Face of the Earth* (trans. by Sollas and Sollas), Vol. II, pp. 123-8, esp. Fig. 14, p. 125. See also R. Douvillé, "La peninsule ibérique. A—Espagne," *Handbuch d. Regionalen Geologie*, Vol. 3, Part 3, Heidelberg, 1911, pp. 138-9.

[40] Sheet 29 (A V).

that to the north.[41] These isolated witnesses of a former southward extension of the Variscan arc lead on southeastward into the thick Paleozoic series of the northern Balkan peninsula.

As far as the writer can judge, this reconstruction of the Hercynian system of geosynclines by Staub is essentially correct in its broader aspects. With this we must now compare the pattern of the Great Alpine geosynclines of Europe. For this purpose, we reproduce another of Staub's diagrams (Fig. 88).[42] A comparison with the

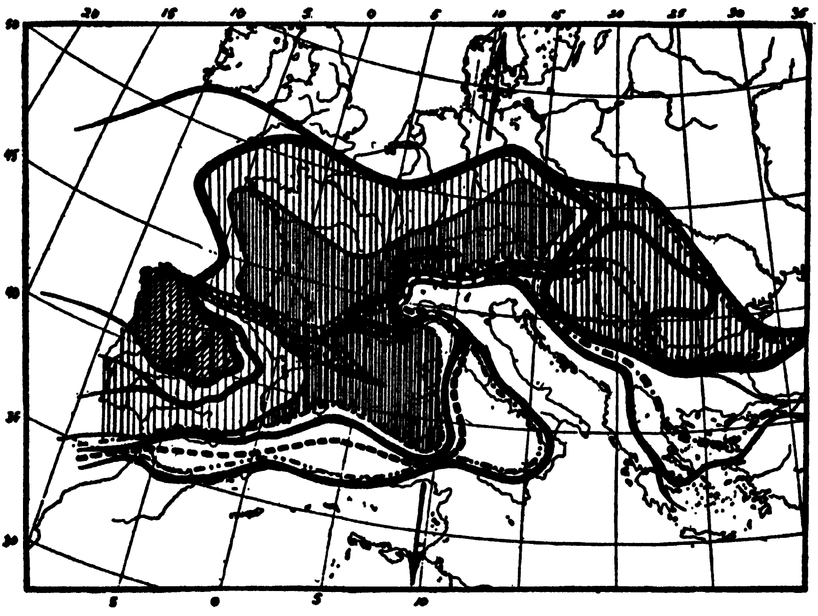


Fig. 88. The axial lines of the Mesozoic-Tertiary (Alpine) mobile belts superimposed on the pattern of the late Paleozoic ("Hercynian") mobile belt of Europe.

Vertical ruling and very heavy black lines = outlines of late Paleozoic mobile belt as shown in Fig. 87; heavy black lines of lesser width = Alpine folded mountain belts; dashed and dotted lines = Alpine geosynclinal axes.

(R. Staub, 1928; reproduced from *Der Bewegungsmechanismus der Erde*, by permission of Verlagsbuchhandlung Gebrüder Borntraeger)

preceding figure will make it easy to separate in this complicated map the lines of the Hercynian and Alpine geosynclines. To familiarize

[41] Quoted from E. Suess, *The Face of the Earth* (trans. by Sollas and Sollas), Vol. IV, p. 158.

[42] Reproduced from Fig. 39, p. 215, of R. Staub, *op. cit.*

himself with the latter, as here represented, the reader should trace the lines through the following regions: Pyrenees and outlying branches in southern France; the double line which touches Spain in the Betic Cordillera and the Balearic Islands on the north, and skirts the north coast of Africa from the Rif to northeastern Constantine; their continuation in the Apennines; the Alps bifurcating at the eastern end; the Carpathians; the Transylvanian Alps; the Balkan Mountains; the Dinaric chains.

The only one of these lines which is hypothetical, that which connects the Balearic Islands with the rest of the Alpine mobile belt, does not concern us here.

This diagram shows convincingly how independent the system of Alpine geosynclines is of that of Hercynian age. In two places, in Asturias and at the eastern end of the Alps, the younger system cuts across the older one as neatly as any "fault trough" anywhere may cut across older folded structures.

For the early Paleozoic geosynclines the record is still more fragmentary. But there is some evidence that a branch of the Caledonic system of mobile belts extended southeastward across northern Germany and was intersected by the Hercynian system within the present boundaries of Poland.[43]

The intersection of the Hercynian mobile belt with the Caledonian in southern Wales was described as early as 1846 by Sir H. T. de la Beche in such masterly fashion that nearly forty years later Suess based his description of this region largely on his memoir.[44] Recently Bailey has given a graphic account of this "crossing of Caledonian Mountains by Hercynian" in his presidential address before the Geological Section of the British Association for Advancement of Science.[45] Following the two systems across the ocean, he has pictured

[43] M. Limanowski, "Sur le croisement successif des chaînes de l'Europe centrale en Pologne et sur les lignes analogiques de ces chaînes," *Bull. Service Geol. Pologne*, Vol. I, Varsovie, 1920-1922, pp. 579-600. Note especially the sketch map, Fig. 1, p. 583. The interpretation of the direction of the main axis of the Hercynian system differs somewhat from that of Staub, but shows the same sharp intersection with the Alpine system.

[44] E. Suess, *The Face of the Earth* (trans. by Sollas and Sollas), Vol. II, p. 84.

[45] Glasgow meeting, September 10, 1928. Reprinted in *Pan-Am. Geologist*, Vol. 50, 1928, pp. 161-88.

a hypothetical corresponding intersection in New England and New York, both in words and on a tectonic map.[46]

Law. It is evident, then, that successive "mobile belts" may cut across each other as sharply and independently as "fracture belts of low mobility," intersect preexisting folds. This is a fact of fundamental importance.

Law 37. When in the same general region a new mobile belt comes into existence after an older one has ceased to function, the newer may intersect the older at any angle.

Interpretation. Stille has proposed to apply the term "renegade folds" to such orogenic zones as break away from the traditional lines of folding.[47] He also pointed out that in contrast to progressive folding adjacent and parallel to the axes of earlier deformation, the mechanics of these "renegade" belts offer a difficult problem.

The customary statement that they indicate a change in the direction of orogenic pressure does not strike at the real problem at all.[48] On the whole, the folds merely mark the site of a geosynclinal furrow which opened up across the older lines of folding to receive conformable sediments often for long geological periods. More than that. It is the major geosynclines of our great orogenic belts themselves which behave in this fashion, and with them the major welts.

It is the large scale on which this law has operated and its universality which give it truly decisive significance. The concept of an alternately expanding and contracting crust has been based so far essentially on the pattern and the deformational history of coexisting mobile belts. Here we find that law 37 leads independently to the same concept.

The traditional view of earth deformation interprets all diastrophism as the result of continuous crustal compression varying merely in intensity but not in sign. To the writer it seems that the changes wrought by incessant crustal compression should reflect the continuity of the process. The geosynclinal furrows of one time should grow out of the pattern of the folds formed in the preceding orogenic deformation in such a way as to reflect the cumulative effect of slowly

[46] *op. cit.*, p. 173 (map).

[47] H. Stille, *Grundfragen der vergleichenden Tektonik*, Berlin, 1924, p. 41.

[48] Stille, *op. cit.*, p. 260.

shifting crustal stresses. Suess' term "posthumous" folding, in fact, was coined for just the sort of relation one should expect.

Stille's analysis of crustal deformation is based on the traditional view of continuous crustal compression. He believes that an explanation for the "renegade" formation of furrows may be found in the rigidification of the older orogenic zones through the process of folding. As the older mobile zones lose their mobility, other portions of the crust begin to yield which before had been protected from, or, as Stille puts it, "inaccessible" to the crustal stresses.

On an earlier page the writer has tried to show that the idea that folding "rigidifies" the crust, is applicable only to the outermost portion of the crust and cannot have any important bearing on the problem of the localization of the major zones of deformation (pp. 201-3). If this view is justified, Stille's interpretation is not tenable in the form in which he has given it. When, however, we change the sign of the stresses active between orogenic phases from plus to minus, Stille's explanation becomes identical with that which was formulated on page 203 to account for the presence of "rigid" "Zwischengebirge." Then, the new geosynclinal furrows mark the location of zones of fracturing or plastic yielding under crustal tension. As such they may arise entirely independent of the structural lines produced during preceding orogenic epochs. For there is a fundamental difference in the way the crustal materials react to pressure and to tension. Slight changes in the physical character and distribution of materials suffice to cause large shifts in the position of tension fractures on a sphere. The crustal wrinkles produced by compression, on the other hand, tend to perpetuate themselves. Large changes are, correspondingly, required to cause important changes in the alignment of crustal folds.

If this reasoning is valid, law 37 offers the most convincing argument in favor of the dualistic concept of crustal deformation here developed.

Opinion 29. The independent manner in which a new mobile belt may intersect the folds of an older one indicates that the formation of the furrow which initiates the new mobile belt is the result of a tearing across the older structures, that is, of tensional stress.

Wichita-Arbuckle and Ouachita Mountains. Before leaving this subject, let us turn to another problem of North American orogeny,

the relation of the Ouachita and Wichita orogenic belts. The setting of these two belts within the structural features of the south-central States is shown in Fig. 89, reproduced from the valuable summary recently published by Van der Gracht.[49]

The main map combined with the small map inserted in the lower left-hand corner will serve well for a concise statement of the problem.

The thick geosynclinal limestones of earlier Paleozoic age (chiefly Cambro-Ordovician) in the Wichita-Arbuckle orogenic belt (the "Wichita" system of Van der Gracht) appear in the same facies as the beds of corresponding age in the Appalachian geosyncline of northwestern Alabama and eastern Tennessee. It is natural to look for a direct connection between the two geosynclinal areas.

But where formations of the same age come to light in the southern part of the Ouachita Mountains in Oklahoma and Arkansas, they appear in entirely different facies, practically free from limestone. The same clastic "Ouachita" facies is found wherever the drill has reached down far enough along the buried continuation of the Ouachita system in eastern Texas (see Fig. 89). The problem is: Where lay the hypothetical geosyncline which connected the Wichita system with the Appalachians? Or, in general, what relation exists between the two systems?

The earlier Paleozoics in the Ouachita facies, so far as they are exposed, lie in the flat-lying thrust sheets which constitute the major part of the Ouachita Mountains. These thrust sheets have overridden the Wichita geosynclinal belt from the southeast. The field relations leave no room for doubt concerning this relation.[50] Fig. 123, especially the insert map, show it graphically. Originally, therefore, the earlier Paleozoic rocks of the Ouachita facies all lay farther south than now. How much farther south?

Van der Gracht, following the present tendency prevalent in Europe, assumes[51] that they have been carried northward hundreds of

[49] Reproduced from Fig. 1, p. 993, of W. A. J. M. Van Waterschoot van der Gracht, "Permo-Carboniferous Orogeny in South-Central United States," *Bull. Am. Asso. Petrol. Geol.*, Vol. 15, 1931, pp. 991-1057 (written with the collaboration of C. L. Baker, F. A. Bush, C. L. Dake, B. H. Harlton, F. H. Lahee, Sidney Powers, J. A. Waters and others; see footnote, p. 992).

[50] See summary in Van der Gracht, *op. cit.*

[51] Van der Gracht, *op. cit.*, p. 999-1000.

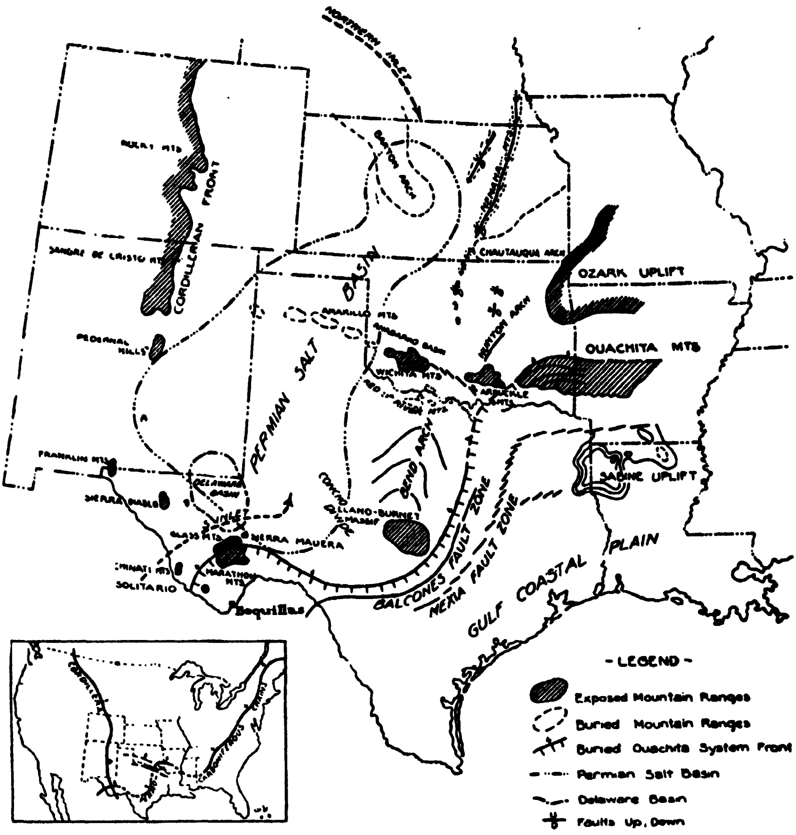


Fig. 89. Tectonic sketch map of the south-central part of the United States. Width of area shown on map, approximately 1,400 miles.
(Van der Gracht and Sidney Powers, 1931)

miles across the Wichita orogenic belt. He considers it probable that the Sabine uplift in northwestern Louisiana actually marks the continuation[52] of the Wichita-Arbuckle system.

[52] On the original map from which Fig. 89 is a reproduction, the Sabine uplift is labelled "Wichita autochthone." This expression was eliminated in this reproduction since it represents merely a hypothetical suggestion. ("Possibly, though as yet there is no means of knowing, the conspicuous positive element of the Sabine uplift, which lies exactly in the trend of the Wichita chain, may be connected with it," speaking of the Wichita system. Van der Gracht, *op. cit.,* p. 1000).

This means that the rocks now forming the visible Ouachita thrust sheets and their buried southwest continuation, originally lay along a line which connects the southern end of the exposed Appalachian system in northern Alabama with the southernmost point of the buried continuation of the Ouachita system south of the Llano-Burnet massif (see Fig. 89, esp. inset map). All rocks that now lie northwest from this line would rest as a foreign thrust mass on top of the buried, unknown "autochthone" according to this concept.

The facts of the field, so far as known, do not favor this view. The thrust planes of the Ouachita Mountains which are so clearly established in Oklahoma seem to die out a short distance east of the Arkansas line. Special search for evidence of their continuation failed to find any.

Furthermore, the general aspect of the details of structure, the relatively open character of many folds, the relative simplicity of the fold pattern seem contrary to the assumption of thrusting on the vast scale demanded by Van der Gracht's hypothesis.

If this conclusion is justified, the original position of the highest of the Ouachita thrust sheets must be sought at a more moderate distance south from their present location, certainly north of what is today the Sabine uplift. In that case, the eastern continuation of the earlier Paleozoic geosyncline of the Wichita-Arbuckle system must have existed somewhere beneath the folds of the present Ouachita Mountains.

We must remember that the trend lines shown on the main map of Fig. 89 were established during the late Paleozoic orogeny. We can only guess at the possible location of the Cambro-Ordovician geosynclinal axis. In fact, we are not even certain that a pronounced geosynclinal furrow extended far east of the present Arbuckle Mountains. Since the limestone facies of the Wichita system is that of the foreland and underlies the plateaus of Oklahoma as well as those of Tennessee, the similarity of the geosynclinal development of these limestones in Alabama and Oklahoma requires no actual connection between the two geosynclines.

We may assume, then, that the axis of the Wichita-Arbuckle geosyncline continued in an easterly direction beyond the present east

end of the Arbuckle Mountains to an unknown distance. When a new geosynclinal axis came into existence toward the end of the Mississippian time, the Ouachita geosyncline, it followed the same general trend in the eastern portion, but turned off abruptly toward the south, cutting across the older axis at right angles, so that in the final period of overthrusting the Pennsylvanian rocks of the Ouachita geosyncline were thrust across the southeastern end of the Wichita-Arbuckle axis.

While the new Ouachita geosyncline was being formed, the older Wichita-Arbuckle belt also developed furrows, but on a smaller scale and after a different manner. As a result, the two regions offer an excellent illustration of a homogeneous and a heterogeneous mobile belt lying end to end and undergoing deformation more or less simultaneously.

The post-Mississippian furrow of the Ouachita region had the character of a homogeneous geosyncline. The sediments in it are similar in thickness and facies along the whole exposed length of the geosyncline and beyond it so far as the drill has reached them.[53] At right angles to the strike both the physical character of the sediments and their thickness change only gradually.

When crustal compression deformed this geosyncline, it yielded in such a way as to form large thrust sheets, some at very low angles, with marginal folds fringing them. Fig. 89 shows the location of these thrusts in a diagrammatic fashion. The buried front of the strongly deformed belt[54] is indicated by the hachured line which runs west of and approximately parallel with the Balcones fault zone of much later date.

[53] Six thousand to 10,000 feet of mostly blue Stanley shales and slates with intercalated thin-bedded, fine-grained dark-colored sandstones; over 6,000 feet of Jackford sandstone; over 9,000 feet of Atoka sandstone and shale; and a similar thickness of post-Pottsville Pennsylvanian formations in the Ouachita Mountains. See, e.g., the isopach maps in M. G. Cheney, "History of the Carboniferous Sediments of the Mid-Continent Oil Field," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 13, 1929, pp. 557-94, Figs. 2 and 3.

[54] For an example of the way this deformed belt is revealed in drill records, see M. G. Cheney, "Stratigraphic and Structural Studies in North-Central Texas," *Texas Univ. Bull. 2913*, 1929.

The thrust-faulted belt comes to light again in the Marathon region[55] and in the smaller Solitario uplift[56] where the stratigraphy still resembles closely that of the Ouachita Mountains. There can be no doubt about the essential continuity of the whole belt as suggested in Fig. 89.

The early Paleozoic geosyncline of the Wichita-Arbuckle region seems to have been also essentially of the homogeneous type. In it from Ozarkian to Mississippian time, limestones accumulated similar to those deposited on the surrounding portions of the Mid-Continent region, differing merely in thickness, with a total thickness of over two miles[57] in contrast to a total of merely 1,000 to 1,500 feet in the surrounding regions. The writer knows of no finer example of a furrow forming without the rise of a complementary welt.

The late Mississippian diastrophism, however, transformed this belt into the structural pattern of a heterogeneous geosyncline. High blocks, in part bounded and traversed by normal faults, came into existence, alternating with deep basins in which Pennsylvanian sediments accumulated to great thickness, such as the Anadarko basin[58] northeast of the Wichita Mountains and the Ardmore basin[59] south of the Arbuckle Mountains.

Accordingly, both thickness and facies undergo rapid changes at right angles to the strike and to a certain extent even parallel with it. As in the Coast Ranges of California, intense folding affected chiefly the deep basins when compression set in, preserving the steep attitude of the major fault planes.

As in the Ouachita system, the larger part of this Wichita-Arbuckle system lies buried beneath later sediments, here largely of Permian age. The axis, marked by a line connecting the Criner Hills with

[55] Philip B. King, "The Pennsylvanian and Permian Stratigraphy of the Glass Mountains," *Texas Univ. Bull. 2801*, 1928, pp. 109-45; *idem*, "The Geology of the Glass Mountains," *Texas Univ. Bull. 3038*, 1930.

[56] E. H. Sellards, "Overthrusting in the Solitario Region of Texas," abstr. of paper read before Geol. Soc. America at Tulsa meeting, 1931. Full paper to appear in *Texas Univ. Bull.* (in press).

[57] Most of this thickness, over 9,000 feet, is made up of Cambro-Ordovician limestones.

[58] A. J. Freie, "Sedimentation in the Anadarko Basin," *Oklahoma Geol. Survey, Bull. 48*, 1930.

[59] C. W. Tomlinson, "The Pennsylvanian System in the Ardmore Basin," *Oklahoma Geol. Survey, Bull. 46*, 1929.

the Wichita Mountains, is continued westward in the buried granite hills of the "Amarillo Mountains." Toward the west, evidence of folding decreases rapidly, with block-faulting dominating the structure.

South of this axis and apparently separated from it "by another deep basin, filled with Pennsylvanian and Permian detritus, the drill has again revealed several anticlinal structures, overlying buried pre-Pennsylvanian ridges. They occur along Red River, particularly in northern Texas, in *échelon* alignment, following the same Wichita strike."[60]

These buried ridges bring to mind the Nemaha Mountains[61] and parallel structural axes which run from northern Oklahoma into Nebraska (see Fig. 89). Their trend is at right angles to that of the Wichita-Arbuckle system. They seem to represent a belt of still lower mobility, dominated primarily by normal faulting. Their relation to the major orogenic belts of this region is still uncertain.

We may sum up the conclusions reached concerning the relation of the Wichita-Arbuckle and Ouachita orogenic belts as follows:

The Cambro-Ordovician geosyncline of the Wichita-Arbuckle system must have extended eastward beyond the portion now exposed, probably essentially along the belt now occupied by the Ouachita Mountains. At the beginning of Silurian time, the geosynclinal deepening of this tract ceased almost entirely. Near the end of Mississippian time, a new geosynclinal furrow came into existence, that of the Ouachita system. It paralleled the Cambro-Ordovician furrow in its eastern part. East of the present Arbuckle Mountains, it turned abruptly southward, continuing into east-central Texas and from there to the present Marathon region. Narrower furrows branched off, by "virgation,"[62] into the western portion of the earlier geosyncline, which assumed the character of a heterogeneous geosyncline with normal faults bounding higher blocks which separated the furrows. Repeated epochs of crustal compression produced the heterogeneous folding in the Wichita-Arbuckle system, while the rocks of the homogeneous geosyncline broke into thrust sheets which pushing

[60] Van der Gracht, *op. cit.*, p. 1015. For further detail the reader is referred to Van der Gracht's paper and the original detailed literature on which it is based.

[61] See p. 253, footnote 96.

[62] See p. 80.

north and northwestward, overrode the eastern portion of the earlier (Cambro-Ordovician) furrow.

Before leaving the discussion of this fascinating region, attention may be called to the intersection of the Rocky Mountain "Cordilleran" orogenic belt with that of the Ouachita system in western Texas. Here, at the southwestern border of the Marathon uplift, the southwest-trending Paleozoic folds of the latter are cut off by the folds and thrust faults of Cretaceous rocks with north-northwesterly strike, the marginal folds of the Cordilleran orogenic belt (see Fig. 89). The structural relations are too complex and too little known in sufficient detail to enable us, at present, to get a clear picture of this remarkable intersection of two orogenic belts.

2. Zonal Migration of Furrowing and Folding

Zonal migration of furrowing. The opening-up of "renegade" furrows has been the exceptional event in the progress of crustal deformation. When it took place on a large scale, it marked the "birth" of a new mobile zone and generally also the "death" of an old one. Within the life of one and the same mobile belt, on the other hand, sedimentation was generally resumed after each orogenic phase in furrows which lay parallel with and adjacent to the lines of welts along which folding had taken place. One might call them "loyal" or "conforming" furrows in contrast to the "renegade" type.

Law 38. When geosynclinal sinking is resumed after an orogenic epoch during the life of a given homogeneous belt, the axis of the new furrow tends to parallel the earlier one but appears displaced with reference to it.

The hypothesis presented in this book assumes that furrows owe their origin to tensional stresses in the crust, that they mark lines along which tensional yielding reaches a maximum, comparable to the localized thinning of a steel bar under tension (cf. Fig. 31). The typical association of welts with furrows is explained by the upward and outward component that is introduced into crustal deformations by the presence of the furrows when crustal compression takes the place of crustal tension. Instead of the rising welts creating the furrows, it is thought that the furrows cause the rising of the welts.

If we accept this hypothesis concerning the relation of welts and furrows, law 38 must mean that the crust tends to continue to yield

along the older lines of yielding whenever crustal tension takes the place of crustal compression, that is, more or less alongside the newly formed welts.

Such a behavior may seem natural enough. Unfortunately, we do not possess mental pictures of the manner in which a strong, non-brittle shell would yield when put under tension. We are especially unfamiliar with the localized character of the yielding. Yet when sheets are put under tension in the course of industrial testing, localized tearing seems to be the rule.[63] All we can say, at present, is that the law 38 seems consistent with the hypothetical picture of crustal deformation developed in this book.

The more or less parallel displacement of the axes of successive geosynclines within one mobile belt might be called the "zonal migration of geosynclines," using the term suggested by Stille for the analogous process in folding. It is exhibited by all large homogeneous mobile belts. In the Appalachian geosyncline,[64] the axis of greatest thickness of sediments was shifted distinctly westward from the Algonkian (Glenarm series), to the Lower Cambrian, the Middle Paleozoic, and finally the later Pennsylvanian. Similarly, there has been a northward displacement of the geosynclinal axis in the Alps from later Mesozoic to the Eocene (Flysch) and finally to the Miocene (Molasse) geosyncline. Grabau has given an interesting description of the Indo-Gangetic alluvial plain as a typical example of a geosyncline displaced southward with reference to the older Himalayan geosyncline.[65]

Zonal migration of folding. The concept of zonal migration of geosynclines carries with it that of a zonal migration of folding. New folds must rise in the latest geosyncline when compression is resumed. This is true especially of marginal folding which reaches farther out into the sediments in front of a rising welt with each compres-

[63] See E. Seidl, *Bruch- und Fliess-Formen der Technischen Mechanik,* Band III, "Zerreiss-Form," Berlin (VD I Verlag), 1930.

[64] In the restricted sense of the term suggested by Schuchert, i.e., south of Vermont, "Sites and Nature of the North American Geosynclines," *Bull. Geol. Soc. America,* Vol. 34, 1923, p. 172.

[65] A. W. Grabau, "Migration of Geosynclines," *Bull. Geol. Soc. China* (Peking), Vol. 3, 1924, pp. 154-69.

sional phase. Waste from the older folds forms part of the later sediments which themselves lie thrown into folds by the later orogenic phase. This relation is so universal that we need not enter into a description of examples.[66]

3. Posthumous Folding

Suess first applied the adjective "posthumous" to anticlinal folds which rise on the site of earlier anticlines of a vanished mountain system with which they agree in trend. The folds of the Paris-London basin still offer the best illustration for this original use of the term. The two largest of these are shown on any geological map of Great Britain and northwestern France.[67] The northern anticline, really a composite of several, forms the oval Weald, surrounded by the bold escarpment of the chalk downs. The larger part of the southeastern third of the oval lies covered beneath the Channel. Only the extreme end is visible again on the coast of France in the vicinity of Boulogne. The southern anticline carries Upper Jurassic rocks to the surface along a long belt in the Pays de Bray, some one hundred kilometers northwest of Paris. This axis of folding also reaches the Channel and is continued in the southern part of the Isle of Wight and westward along the English shore to Weymouth.

West of the plain of Somerset and in Devonshire the peneplained folds of the Hercynian mountain system emerge from beneath the Mesozoic sediments of the Paris-London basin. The geologic map shows that they constitute two major anticlinal belts of Devonian rocks separated by a major synclinal axis of Carboniferous rocks. The northern border of this ancient mountain system emerges from beneath the Mesozoic cover as the anticline of the Mendip Hills, north of the plain of Somerset. In the eastern part of the Mendips the overthrusting and the zigzag crumpling of the overridden coal-measures resemble greatly the structural conditions in the Belgian coal fields. This resemblance was recognized as early as 1824 by Buckland and Conybeare. In 1855, Godwin Austen published a paper "On the

[66] See, e.g., in E. O. Ulrich, "Revision of the Paleozoic Systems," *Bull. Geol. Soc. America*, Vol. 22, 1911, the remarks on "inland migration of Appalachian belts of folding," p. 435, and discussion on later pages.

[67] See, e.g., sheet 23 (B IV) of the *Carte géologique internationale de l'Europe*.

Possible Extension of the Coal-Measures beneath the Southeastern Part of England."[68]

In this famous paper he pointed out what the geological map shows so impressively: That the folds of the Weald lie midway between the overthrust Carboniferous folds of the Mendip Hills in southwestern England and those of the coal fields of northern France and Belgium, and that they coincide closely in strike with the line connecting the two. He saw in these later, weaker folds a revival of the older axes of disturbance. Their presence to him constituted a sort of proof of his conclusion that beneath the later sediments of the London basin the folds of the ancient Hercynian system continued uninterruptedly from Belgium to the Bristol Channel.

This example was generalized by Godwin Austin into the law "that when any zone of the earth's crust is considerably folded or fractured, subsequent disturbances follow the previous lines, and this simply because these lines appear to be lines of least resistance."[69]

The reason assigned for this behavior in the last words of the preceding quotation is interesting. It is the opposite of what is frequently stated in geological literature, that folding renders a series of strata more rigid. It emphasizes the vagueness of our talk about the "rigidity" of rocks under stress.

Commenting on this type region of "posthumous folding," Suess wrote: "It is very likely that in most other mountain systems repeated movements in the same direction have occurred at very different times; but seldom do we witness so striking an episode as is here presented in the subsidence of a great segment of a mountain arc between successive periods of folding; and in this example we find clearly displayed the extraordinary constancy in the direction of the folding force."[70]

This was written in 1888. Twenty years later, in the fourth volume, Suess had to admit that the relations between the older and the newer folding are by no means as simple as they had seemed in the light of

[68] R. Godwin Austen, "On the Possible Extension of the Coal-Measures beneath the Southeastern Part of England," *Quart. Jour. Geol. Soc.*, 1856, Vol. 12, pp. 38-73. Quoted from E. Suess, *The Face of the Earth* (trans. by Sollas and Sollas), Vol. II, p. 91. See Suess' account, *ibid.*, pp. 87-97, for more structural details.

[69] The quotation is from E. Suess, op. cit., pp. 93-4, the original being unavailable to the writer.

[70] E. Suess, *op. cit.*, pp. 95-6.

less information.[71] It had been found that the Hercynian folding extends into the coal fields north of the Bristol Channel. The Mendip Hills can no longer be called the northern border of the Hercynian system of folds. In view of the divergent (northeast) strike of the more northerly folds the assumption seems no longer safe that beneath the cover of later sediments they connect in a simple arc with those of northeastern France.

But worse still, south of the two major axes of later folding, those of the Weald and of the Pays de Bray, similar lines of disturbance with the same northwest strike are found in the southern part of the Paris basin and even along the northern border of the basin of Aquitania, that is, south of the axis which connects the Hercynian region of Brittany with the Central Plateau. Here they are unmistakably connected with faults and quartz dikes (one 140 kilometers long) which cut into the old Hercynian masses and partly bound them after the fashion of faults in and along a "horst" or "block mountain." Speaking of the southwestern border of the Central Plateau and its structural continuation in the "Strait of Poitiers," Suess finds it difficult "to distinguish between faults, which emerge from horsts, and posthumous folds, when they follow nearly the same direction."[72]

Here, then, 500 kilometers southwest of the Weald axis of folding, we find the later folds tied genetically to lines of faulting cutting the basement rocks at angles to the older structural trends. Going 500 kilometers in the opposite direction, northeast from the Weald axis, we find ourselves in the midst of the classical region of "fault-folds," northeast of the Harz Mountains. Here the younger folds strike also northwestward as in the Paris basin, and as in its southern part they are closely tied to the faults that bound the fragments of the Hercynian basement that rise into view. But here the strike of the late folds cuts across that of the Hercynian structures. Yet in strike and dimensions the Harz with the folds in its prolongation is comparable to the Weald folds. If the latter had been arched higher, the Hercynian rocks would have formed a counterpart to the Harz. Clearly, the folds of the London-Paris basin are part of a much broader movement. Why coin a term for that case where accidentally the earlier

[71] E. Suess, *The Face of the Earth* (trans. by Sollas and Sollas), Vol. IV, pp. 42-53.
[72] *op. cit.*, Vol. IV, p. 45.

direction of folds coincides with that of later folding? Suess himself recognized that the trend of the "posthumous" folds of the London-Paris basin is dictated by that of the "horsts" that surround it. But the trend of these elevated portions of the Hercynian substructure is not merely a revival of old directions of folding, but is the result of new trend lines, which in the Variscan part of the Hercynian system cut squarely across the older folds.

Folds in a mantle of younger sediments are caused by a deformation of the crustal substructure. To apply the term "posthumous" to them is apt to interfere with rather than help the understanding. To be really significant, the term should be used for a revival of ancient crustal folds. The Blue Ridge-Green Mountain axis of the Appalachians and the Highlands of Scotland and Scandinavia stand on the face of the earth today as "posthumous" welts. The seemingly simple and gentle arching that characterizes them does not correspond to what is commonly called "folding." Yet no one is prepared to say what their structure would look like if the "posthumous" movement that created their present form had been recorded in the attitude of a thick sedimentary cover.[78] According to the geometrical definition adopted in this book, their creation was an act of orogenesis. It is instructive to call it "posthumous." Yet nothing of fundamental importance is comprised in that term, even in this use. Godwin Austen's "law" does not state a generalization of major importance for the understanding of the history of mobile belts. Everywhere wider studies show that regional stress relations within the crust dictate primarily where furrows shall sink and welts with their marginal folds shall rise. This dominating control of regional crustal stresses is reflected in the successive patterns of furrows and subsequent folds. To this we turn once more.

4. Similarity and Regional Proximity of Patterns of Older and Newer Mobile Belts

Europe. A careful examination of Staub's map diagram, Fig. 88, shows a remarkable similarity between the pattern of the Hercynian and Alpine geosynclinal belts. Both consist of an east-west trending central portion with a more or less meridional stretch at both ends

[78] See, e.g., M. R. Campbell's studies of warped old river gravels in *Bull. Geol. Soc. America*, Vol. 44, pp. 553-73.

which returns to the east-west direction in a more or less conspicuous loop. The western loop of the Hercynian system, which traverses the Iberian peninsula, has its counterpart in the ranges that swing from Sicily through Italy into the Ligurian Apennines. The largely hypothetical meridional branch which connects the Hercynian folds of Asturias with southern England corresponds to the meridional portion of the Alps, from the Maritime to the Pennine Alps. Staub's map suggests that the Hercynian folds of southern Ireland represent a separate branch leaving the main stem by virgation. In his book, he points out that this offshoot, as he sees it, occupies a position comparable to that of the Pyrenees and their continuation in southern France with reference to the Alps.

The map shows a similar virgation of the Hercynian system in the eastern Sudetes. The evidence for this virgation seems quite convincing. The northern branch, though partly concealed, leads from the northeastward striking folds along the eastern border of the Sudetes, south of Breslau, to the Hercynian folds of Poland, in the region of Kielce[74] and probably far beyond. The southern branch was discussed above on page 361. The Alpine system bifurcates in a similar manner at the eastern end of the Alps, the one branch leading into the Carpathians, the other into the Dinaric chains and their continuation southward through the Balkan peninsula into Asia Minor.

With all due skepticism concerning the details of these lines, there can be no doubt about the generic similarity between the two patterns. It is most remarkable that the later pattern appears shifted bodily toward the southeast.[75] This lateral displacement constitutes the most impressive illustration of the validity of law 37.

The later system of geosynclines establishes itself by cutting indiscriminately here across the trend lines of the earlier folds and there across what was "rigid" foreland in Hercynian times. This shows convincingly that not an inherent "rigidity" or "mobility" of the crust

[74] See the discussion in S. von Bubnoff, *Geologie von Europa*, 2. Band, 1. Teil, 1930, pp. 516 and 540-2, and esp. the beautiful tectonic maps in Fig. 157, p. 509, and Fig. 200, p. 665.

[75] M. Limanowski, "Sur le croisement successif des chaines de l'Europe centrale en Pologne . . . ," *Bull. Service Géol. de Pologne*, Vol. I, Varsovie, 1920-1922, p. 594; "Tout ce qui précède nous démontre que les chaines de l'Europe centrale se sont edifiées suivant un même plan qui, au cours des siècles, fut transposé vers le sud et vers l'est."

in different regions, but regional stresses affecting the crust at large determine the location of the new mobile belts; that the two patterns turned out to be as similar as they are, in spite of the lateral displacement of the one with reference to the other, can only mean that in its largest aspect the distribution of the stresses in the crust depends on the physical properties of the crust at large and on the nature of the processes involved, both of which remained unchanged.

North America. In 1849 Dana wrote, all continents "have had their laws of growth involving consequent features as much as organic structures."[76] In his presidential address before the American Association for the Advancement of Science in 1855[77] he dwelt on the simplicity of the form of the North American continent, that of the triangle, the simplest of mathematical figures. He visualized it as a block wedged between the oceans, wrinkled along its margins. Since this presentation, American geologists have been accustomed to think of continental growth, especially that of North America, as due to marginal accretion. This picture implies precisely that similarity between the patterns of older and younger orogenic systems and that proximity in space which we see realized in Europe.

In 1890, Dana wrote concerning the North American continent: "The areas of rock-making were defined for the most part in Archean time; their confines were old Archean ranges, or else later uplifts made in accordance with the Archean system."[78] This idea was recently treated elaborately by Ruedemann.[79]

It seems that this emphasis on the controlling influence of the early structural lines, the "grain" of the continent, implies a far too simple relation of later to earlier orogenic movements. It conceals the fact of the essential independence of later lines expressed in law 37. That the "grain" influences the details of the pattern of later crustal

[76] J. D. Dana, in *U.S. Explor. Expedition, under the Command of Charles Wilkes, U.S.N.*, Vol. X, Philadelphia, 1849, p. 436. (Quoted from Dana's paper on "Areas of Continental Progress in North America . . . ," *Bull. Geol. Soc. America*, Vol. 1, 1890, p. 48.)

[77] *idem*, "On American Geological History," *Am. Jour. Sci.*, 2nd ser., Vol. 22, 1856, pp. 305-34.

[78] *idem*, "Areas of Continental Progress in North America . . . ," *Bull. Geol. Soc. America*, Vol. 1, 1890, p. 48.

[79] Rudolf Ruedemann, "The Existence and Configuration of Pre-Cambrian Continents," *N.Y. State Mus., Bull. 239-40*, pp. 67-152, esp. pp. 84-93; "Fundamental Lines of North American Geologic Structure," *Am. Jour. Sci.*, Vol. 6, 1923, pp. 1-10.

deformation is a foregone conclusion. But the more complicated and therefore more decisive example of the Hercynian and Alpine geosynclines proves that it does not create it. The similarity between the patterns of earlier and later mobile belts constitutes a problem which is fundamentally independent of the results of earlier orogenic movements. Our understanding of the structure of the North American continent can only gain from the recognition of this fact and the search for its evidence.[80]

Asia. One cannot read Suess' fascinating account of the structure of Asia in the third volume of his *Antlitz* or Argand's great paper on the same subject before the International Congress at Brussels without being impressed by the unity of plan which results from the similarity and regional proximity of the successive patterns of the orogenic belts. It is such that Suess speaks of the "wonderful arc-producing power which emanates from the vertex of Eurasia."[81] Yet Suess' own account abounds in examples of the far-reaching independence of older and newer orogenic trend lines expressed in law 37.

Suess thought of the pattern of crustal folds as analogous to that of waves travelling across the surface of a fluid. This view arose primarily from the contemplation of the pattern of the orogenic belts, especially of the long free-branching folds in which some of the great belts die out. Thus he thought of "a resemblance between the waves of Krakatoa which encircle the earth and the long arms of the Altaides."[82]

But he saw his view no less confirmed by the similarity between older and newer patterns. In the second volume of the *Antlitz* he compared the sharp curve of the Hercynian folds in Asturias with

[80] In the south-central United States, for instance, the Mississippi embayment with a north-northeast-south-southwest strike, intersects the Ouachita folds with an east-west trend. The great arc in which the Ouachita system swings from an east-west trend into one directed from north to south, cuts across the west-northwest-east-southeast strike of the Wichita-Arbuckle system. A short distance to the north lie the buried hills with axes trending a little east of north. Ruedemann pictures the old "grain" of the basement complex as trending east-southeast-west-northwest in the Ouachita region and swinging around into a northwest direction toward the west. Fath and others after him assume the ancient grain to be reflected by the north-south trending buried ridges of Oklahoma and Kansas. Obviously, not all these directions can represent the unknown "grain" of the crystalline basement, and the later movements must have been largely independent from it, whatever its trend may be.

[81] E. Suess, *The Face of the Earth* (trans. by Sollas and Sollas), Vol. III, p. 146.

[82] *ibid.*, Vol. IV, p. 508.

that of the Alpine folds at Gibraltar. He wrote: ". . . indeed an entirely new problem now presents itself. For we have here not simply an ancient mountain range followed by a new one, folded in the same direction, but an ancient circumflexure followed by a new circumflexure. The region of recurvature has been displaced southwards . . ."[83] about eight degrees of latitude. Commenting on this observation, he wrote thirteen years later: "It is hard to conceive how such a curve could be formed a second time, unless we assume the existence of some kind of wave propagating itself freely through the crust of the earth."[84] Here, as in so many other ways, Suess demonstrated his mastership in recognizing and formulating the fundamental problem of earth structure.

Australia. It is not accidental that Suess' idea of "waves propagating themselves in the crust of the earth" should, among contemporaneous geologists, be followed especially by an Australian master. For Australia offers a particularly impressive picture of simple orogenic belts of similar trend successively displaced toward the Pacific Ocean. Correspondingly, Andrews pictures the mountains "with the progressive passage of time . . . extended outward successively in space as rings from the (continental) nuclei."[85] He sees in this arrangement "a creeping," or "rock flowage," toward the great ocean basins ". . . which takes place in a manner such that the flowage was reflected as undulations at the surface. These undulations were mutually supporting, the vertical relief being slight compared with the horizontal distance between the waves or undulations, as in the case of other waves of pulsation." "With increasing strength of the crust at the nuclei, the less deeply seated zones of pressure passed outward in confocal undulations to the margins of the unstable areas. . . ."[86]

Conclusion. We are here not concerned with the mechanics suggested by Andrews.[87] The brief reference to his views is here introduced merely to show how profoundly the fact of the similarity and

[83] E. Suess, *op. cit.*, Vol. II, p. 128.
[84] *ibid.*, Vol. III, p. 4.
[85] E. C. Andrews, "Contribution to the Hypothesis of Mountain Formation," *Bull. Geol. Soc. America*, Vol. 34, 1923, p. 386.
[86] *ibid.*, p. 399.
[87] For a further elaboration of his views see A. C. Andrews, "Hypothesis of Mountain-building," *Bull. Geol. Soc. America*, Vol. 37, 1926, pp. 419-54.

regional proximity of successive mobile belts has influenced the thinking of leaders in America, Eurasia, and Australia. It constitutes indeed a law of fundamental importance.

Law 39. New mobile belts when viewed in their entirety in any larger unit of the earth's surface are found to resemble the next older (largely inactive) belts in trend and general pattern and to lie adjacent to or superimposed on them.

In the past, most attempts to understand the mechanics that lie back of this law were made without reference to the facts comprised in law 37, especially the crucial evidence of Europe. Taking these into consideration and following the trend of thought developed in this book we arrive at the following view:

Opinion 30. The creation of a new mobile belt means that the strain produced by crustal tension becomes partly localized along new lines of yielding. A general similarity between old and new lines indicates that the ultimate factors which determine the distribution of stresses in the crust remain the same in successive tensional phases and that they lie in the form and texture of the crust at large and are quite independent of the details of structural trends near the surface.

The writer cannot leave this subject without pointing out that the hypothesis of continental drift, as proposed by Wegener and his followers, offers no help toward an understanding of the facts expressed in laws 37 and 39 combined. Staub realized this fully. His brilliant book is an attempt to combine the idea of continental drift with that of alternating tensional and compressional phases in the earth's crust. Having accepted the hypothesis of floating continents subjected to a westward drift, he had to find a reason for alternate tension and compression along the great east-west belt of the "Tethys," from the Gulf of Mexico through the European Mediterranean to the Malay Archipelago. He introduces hypothetical subcrustal currents, "gewaltige Strömungen," directed alternately toward the poles and toward the Equator. Thus the Alpine belt of geosynclines is ascribed to a post-Hercynian drift to the poles, "Poldrift," of the major continental masses. The Alpine orogenesis, in turn, is ascribed to a renewed equatorward drift, "Polflucht" of the continents.

The reader is referred to the original for the exposition of the main hypothesis and the auxiliary hypothetical assumptions required to complete it. He will not be surprised to find that Staub believes that

the meridional alternating currents can be explained by the "law of isostasy."[88]

As far as the writer can judge, the order of magnitude of the forces invoked by Staub is similar to that of the forces demanded by Wegener. If we grant the latter, we must be prepared to accept the former. As an attempt to combine with Wegener's premises a set of facts at first sight utterly incompatible, Staub's work deserves admiration.

But the writer's objections to Wegener's hypothesis hold good even more to Staub's. If these objections are valid, Staub's Wegenerian hypothetical substructure collapses. But the concrete body of proved facts remains, which Staub attempted to explain. This "Poldrift" and "Polflucht," in that case, appear as nothing else but the alternating phases of crustal tension and compression postulated in the hypothesis here developed.

[88] R. Staub, *Der Bewegungsmechanismus der Erde,* Berlin, 1928, esp. pp. 211-13.

CHAPTER XII

TIME RELATIONS OF MOBILE BELTS

Very few things happen at the right time, and the rest do not happen at all: the conscientious historian will correct these defects.
Mark Twain, in *A Horse's Tale*.

1. Episodic Character of Orogenic Epochs

Introduction and law. All physical knowledge, in the last analysis, rests on measurement of three fundamental quantities: length, mass, and time. This is, of course, true of geology as well as of all other physical sciences, with this qualification, however, that in most geological studies only the relative values of these quantities enter into consideration.

Thus we were concerned, in a large part of these pages, with the dimensions relative to the earth's crust of the orogenic units undergoing deformation. We took care not to neglect depth besides width and length. We introduced the relative mass of crustal units in the discussion of isostatic behavior. We must now study critically the time relations involved in the process of deformation in mobile belts.

Time enters into the problem of crustal deformation in two significant ways: as the duration of a given event, and as a point on the time scale with which the given event coincides. We shall take up first the duration of the act of orogenic deformation in comparison with the length of time between periods of deformation. The relation is sufficiently understood to be expressible in the form of a law.

Law 40a. At any given point on the earth, the epochs of compressive deformation have occupied much less time than the intervals between them.

Law 40b. In some cases, unconformable later sediments prove that each act of folding occupied only a fraction of a geologic period.

Folded Appalachians. The first part of this law expresses the very general observation that below and above a typical angular unconformity lie thick series of conformable beds. In North America this is exemplified on an imposing scale in the Appalachian folds. The belt south of Pennsylvania offers the simplest relations. Here, from Cambrian to Pennsylvanian time, a tremendous thickness of sedi-

ments accumulated. When viewed over large areas, these sediments are far from being conformable in the mathematical sense. The thickness of individual formations varies from point to point and whole groups of formations may be wanting over large areas. Yet through the whole thickness of sediments, measuring several miles, there are no angular unconformities, "the physical relations between such deposits, as revealed within the limits of actual exposure, very closely simulating continuity of deposition even where the breaks are greatest."[1] Nor do the later folds bear a recognizable relation to the shifting of the areas of sedimentation from epoch to epoch. The folding took place after the whole series of sediments now visible had been completed. Across the beveled edges of the folds lie, in Alabama, Upper Cretaceous and Tertiary beds a mile or so thick.

Here, in the folded Paleozoic rocks of the Appalachian Valley from Virginia to Alabama, the structural picture is clearly that of folding as an episode with a definite beginning and end. It began after the last sediments involved in the folding had been laid down and must have come to a complete end before it was possible to cut across the folds the relatively even surface on which the coastal plains sediments rest today, a surface due largely to subaerial degradation smoothed out by the wave action of the advancing sea.

The question at once arises whether the event of folding in this as in all similar cases would appear as simple if there were not so wide a gap in the record. In Alabama that gap extends from near the end of Pottsville (early Pennsylvanian) to the beginning of Tuscaloosa (Upper Cretaceous) time. In the latitude of Harrisburg, Pa., this gap is reduced to the interval between the Dunkard Series (Lower Permian-Autunian) and the Newark series (Upper Triassic-Keuperian), but even that is a very long stretch of time, certainly many times longer than the time consumed in the actual process of folding.

Coast Ranges of California. The remarkable fact is that the folding appears to be a process quite different from the changes of level which produced the conformable sediments above and below an unconformity, no matter how small the time interval is that lies between the latest sediment involved in the folding and the first that trans-

[1] C. Butts, "Variations in Appalachian Stratigraphy," *Jour. Washington Acad. Sci.*, Vol. 18, 1928, p. 380. The whole paper, pp. 357-80, should be read in this connection.

gresses. In many cases this interval is small indeed as stated by the second part of law 40. In the Coast Ranges of California, for instance, a strong angular unconformity separates the Knoxville group of sediments from the Franciscan Group. Fossils of doubtful Upper Jurassic age have been found at several places in the vicinity of San Francisco,[2] the type locality of the "Franciscan." The best fossils were collected farther south on the coast at Slate's Hot Springs in Monterey County,[3] on the west side of the Santa Lucia Range. They were described and figured by C. H. Davis.[4] Five of the seven fairly well preserved molluscan fossils were found to be identical, or nearly identical, with forms occurring in beds in the Queen Charlotte Islands to which Stanton ascribes an Upper Middle Jurassic age. According to Crickmay, they are "certainly Upper Jurassic."[5] The beds in which they were found are "much more faulted and metamorphosed" than the basal beds of the Knoxville group beneath which they dip.

The Knoxville group as a whole is of Lower Cretaceous age. But Haug has shown that several ammonite species from the lower Knoxville are very similar if not identical with forms from the Tithonian (Portlandian) of Moravia. A comparison of the pelecypod species of the genus *Aucella*, from the Knoxville group with those of Russia (by Pavlov) has led to similar results. It seems, therefore, very probable that the lower part of the Knoxville, the *Aucella piochii* horizon, is of late Upper Jurassic (Portlandian) age.[6]

No definite description has been given as yet in print of a locality where the Tithonian portion of the Knoxville may be seen to rest with angular unconformity on the Franciscan. But the way the horizons bearing Portlandian faunas have been assigned unhesitatingly to the Knoxville and not to the Franciscan leaves little room for doubt con-

[2] C. H. Crickmay, "Jurassic History of North America: Its Bearing on the Development of Continental Structure," *Proc. Am. Philos. Soc.*, Vol. 70, 1931, p. 53.

[3] See Lucia quadrangle, California.

[4] C. H. Davis, "New Species from the Santa Lucia Mountains, California, with a Discussion of the Jurassic Age of the Slates at Slate's Springs," *Jour. Geol.*, Vol. 21, 1913, pp. 453-8.

[5] C. H. Crickmay, *op. cit.*, p. 53.

[6] E. Haug, *Traité de Géologie*, Vol. II, 1908-1911, p. 1109. See also J. P. Smith, "Salient Events in Geologic History of California," *Science*, Vol. 30, 1909, p. 347. F. M. Anderson proposed the name "Paskenta" for the upper Knoxville, limiting "Knoxville" to the lower portion. F. M. Anderson, "Cretaceous Deposits of the Pacific Coast," *Proc. California Acad. Sci.*, 3rd ser., "Geology," Vol. 2.

cerning their relation. Recently, "Knoxville" shales bearing Tithonian fossils were found overlain "with gentle discordance" by true Lower Cretaceous beds. This may indicate a second, perhaps milder, episode of this latest Jurassic deformation.[7]

Here, then, we have evidence of two epochs of folding, one of which, perhaps the stronger, took place after the beginning and before the end of Upper Jurassic time, the other at the end of the Jurassic, both separating intervals of seemingly undisturbed deposition.

Western Alps. For one other illustration we turn to the Western Alps.[8] In the interior of the Alps marine Eocene strata are involved in the formation of the great *decken* of the Central Alps. There, all that can be told is that the folding is later than most of the Eocene period and earlier than the details of the present topography. On the southwest side of the lowland of the Po River, however, almost undisturbed Middle Oligocene (Rupelian) beds lie on *decken* which are the structural equivalents of the "Pennine *decken*" of Switzerland.[9] The main deformation in the Western Alps took place, therefore, in the short interval between latest Eocene and Middle Oligocene. North of the "autochthonous Massif"[10] of Mont Blanc, however, Lower Miocene (Aquitanian) beds were involved in the deformation. Here, then, a decidedly later orogenic phase is recorded. Correspondingly, the great masses of pebbles of Alpine rocks make their appearance in the sediments of the Tertiary foreland in Miocene time.

The Miocene beds of the Alpine foreland are themselves folded. This points to a post-Miocene phase of Alpine orogenesis. In the Jura Mountains, the first and chief phase of folding occurred after Upper Miocene beds (Sarmatian) had been deposited which today are seen to be folded conformably with the older formations. On the south side of the Alps, the Miocene beds are likewise folded conformably with the older formations. Here, undisturbed marine Middle Pliocene beds extend up into the valleys eroded in the older folded rocks.

Conformable sedimentation, in the broad sense indicated in the discussion of the Appalachian folds, prevailed from the beginning of the Triassic to the end of the Eocene, along the central axis of the

[7] C. H. Crickmay, *op. cit.*, p. 61. The locality is on Huasna River, California, and was found by N. L. Taliaferro.

[8] Quoted from Alb. Heim, *Geologie der Schweiz*, Vol. II, Part I, pp. 40-2.

[9] See p. 193.

[10] See p. 189.

Alps, to the end of the Oligocene along the northern front of the autochthonous massifs; to the end of the Miocene in the Tertiary foreland and the Jura Mountains; and to the early Pliocene time on the south side of the Alps. This is a good statement, of course, of the migration of the zone of folding along the Alpine "welt." In each case, the sediments overlying the great angular unconformity which records the act of folding, have been little affected (or not at all) by the later movements. Each orogenic movement, at the place where the unconformity is observed, occupied only a fraction of the length of a Cenozoic period.

But does this mean, that as far as the Western Alps as a whole were concerned, each movement was a separate event? The process of folding may have been essentially continuous when viewed over the body of the Western Alps as a whole and merely affected different points at different times. Law 40 would, in that case, be true only for each point studied but not for the orogenic belt as a whole. In view of this possibility the law was worded in the way it is stated above.

Heim, in fact, denies that there was any definite break in the Alpine orogenic movements even during Miocene time, although no angular unconformities have been observed within the Miocene series. He pictures the folding of the Alps as an essentially uninterrupted process.[11]

Westphalian Coal Basin. The idea that "mountain folding" is a long-continued process has been and is being held by many workers in geology. One observation especially has lately brought this view into prominence. As mining and drilling operations open up the knowledge of deeper parts of folded sediments, it is found frequently that at depth steeper dips prevail. The more intense folding at greater depth is interpreted to mean that the process of folding went on simultaneously with sedimentation. The lower beds are assumed to show the highest degree of folding because they have suffered deformation for the longest time.

A very positive statement of this view was made recently by Böttcher in a valuable paper on a part of the Westphalian coal re-

[11] "Die Beweise für eine miocäne Ruhezeit sind meines Erachtens nicht erbracht, höchstens kann man zwei Phasen im gleichen ununterbrochenen Fortgang unterscheiden." Alb. Heim, *op. cit.*, p. 42.

gion.[12] Large-scale mining developments have made it possible to reconstruct the attitude of the coal-bearing formations at depth with greater accuracy than before. In Fig. 90 is reproduced one of the

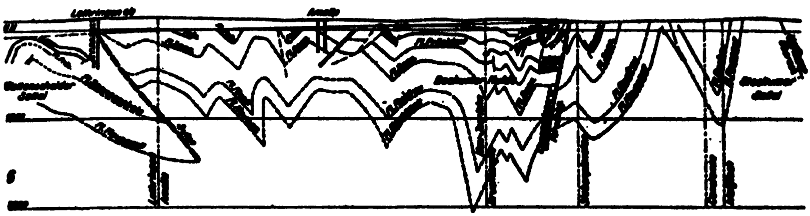


Fig. 90. Structure-section across the coal basin of Bochum, Westphalia. Solid and broken lines = coal seams, known and projected. Vertical double lines = mine shafts; vertical hachured double line = fault zone.
(H. Böttcher, 1925)

nine cross-sections which accompany his paper.[13] The structure is indicated by the coal seams (marked *Fl.* = *"Flötz,"* followed by the name of the seam) which are drawn as solid lines where definitely known, and as dashed lines where their position is inferred.

Note the difference between the structure of the highest and the lowest coal seams in the syncline marked "Bochumer Mulde" (just to the right of the center). The open syncline with gentle dips near the surface is in striking contrast to the sharply pinched structure at depth with its very steep dips. Moreover, where the surface shows essentially but one syncline, there are two major and one minor syncline at depth.

This downward increase in the intensity of folding seems to be typical of the region. Its recognition is of far-reaching prognostic importance for the mining industry.

Examination of the very detailed and accurate mine data upon which the cross-sections are based of which Fig. 90 is one, led Böttcher to the observation that the distance between coal seams is generally greatest at the vertices of synclines. This suggested the possibility that the excess of sediments in the synclines might be

[12] H. Böttcher, "Die Tektonik der Bochumer Mulde zwischen Dortmund und Bochum und das Problem der Westfälischen Karbonfaltung," *Glückauf; Berg- und Hüttenmännische Zeitschrift,* Vol. 61, 1925, pp. 1145-53 and 1189-94 (with geological map in colors showing the intersection of the formations with a plane 200 meters below sea level, 1:50,000).

[13] Reproduced from H. Böttcher, *op. cit.,* p. 1147, Fig. 1, section 5.

due to deposition during the act of folding. In order to test this idea Böttcher compared the distances between coal seams on the vertices of anticlines and synclines with the interval between the same seams at a point on a limb half-way down from the crest of the anticline. Taking the latter thickness as unity, he found the average interval between coal seams on the anticlines 1.22 (for 83 measurements) and 1.85 in the synclines (for 71 measurements).[14] If the increase in thickness were due solely to the act of folding, he argues, it should be the same for anticlines and synclines. Since 63 per cent more rock material appears on the vertices of synclines than on those of the anticlines, this must be due to excess accumulation of sediments in the synclines, that is, folding and sedimentation must have gone on simultaneously.

If this conclusion is sound, it must be taken into serious consideration. Its influence is already evident in geological literature.[15] In a recent study, Bärtling has not only accepted it, but believes that it can be demonstrated that the proportion of sandstones is greater in anticlines than in the synclines[16] which he thinks is further proof of sedimentation having been contemporaneous with folding. This latter conclusion does not follow necessarily, of course. If such a relation between anticlines and sandstones actually exists, we may assume just as well that the limited distribution of sandstones has influenced the localization of anticlines and synclines. The really critical argument is that involved in Böttcher's paper. Its validity rests on the correctness of the assumption that the thickening due to folding should be the same on anticlines and synclines. This assumption can hold good only, of course, if the anticlines are comparable geometrically to the synclines.[17] A glance at Fig. 90 shows that this is not true. In cross-section, the vertices of most anticlines have the shape of broadly rounded folds, while those of the synclines have the form

[14] For details see the table on p. 1190, *op. cit.*

[15] See, e.g., W. A. J. M. Van Waterschoot van der Gracht, letter to Sidney Powers, quoted in *Bull. Am. Assoc. Petrol. Geol.,* Vol. 10, 1926, p. 427.

[16] R. Bärtling, "Das Verhältnis zwischen Sedimentation und Tektonik im Ruhrgebiet," Congrès de stratigraphie carbonifère, Heerlem, 1927 (Liège, 1928). Quoted from abstract in *N. Jahrb. f. Min., etc.,* Referate II, 1929, p. 573 (original not available).

[17] Böttcher's tables give the thicknesses at the vertices for anticlines and synclines with limbs enclosing similar angles. To the writer, however, the geometrical form of the vertices appears far more significant than the angles formed by the limbs.

of acute angles. The contrast is striking and seems ample to account for the difference in the amount of thickening between the two types of folds. The figures obtained by Böttcher, valuable as they are for the practical problems of predicting conditions at depth for mining purposes, do not seem valid as evidence for contemporaneous folding and sedimentation under the conditions peculiar to carboniferous coal swamps.

There still remains, however, the general fact that the folds are more numerous and involve steeper dips at depth than near the surface. Can it be explained in any other way than by assuming that the lower beds have been compressed longer, or at least, oftener than the but moderately folded upper beds?

For an answer we turn to Willis' classical experiments on rock folding.[18] The results of one of his experiments is here shown in Fig. 91.[19] The reader should cover the lower half of the figure imagining it to be unknown, only the upper strata being accessible to observation. A few low-angle and high-angle thrusts and dominantly low dips characterize the visible structure. This is less deformation than appears in the upper two hundred meters of the Westphalian section in Fig. 90, where also low-angle and high-angle thrusts exist side by side. In the experimental model as well as in the Westphalian coal basin the amount of deformation and the steepness of dips increase downward. In the experimental model we know that the downward increase in folding is not due to folding during deformation, but to the struggle for space in the beds below, which cannot escape by the simple device of fracturing as do the beds near the surface. The differential behavior is imposed upon the strata by the presence of a less yielding basal support, which in the case of the experiment was rigid.[20]

Such a behavior at depth was anticipated by Buxtorf when he drew the hypothetical section across the sheared-off folds of the Jura Mountains reproduced in Fig. 37 (p. 156) of this book. The problem

[18] B. Willis, "The Mechanics of Appalachian Structure," *U.S. Geol.. Survey, Thirteenth Ann. Report*, Part II, pp. 217-82.

[19] Reproduced from B. Willis, *op. cit.*, Pl. CMLXVI.

[20] For other good illustrations of this differential behavior see Pls. LXXVIII, XCI, XCV of Willis' work.

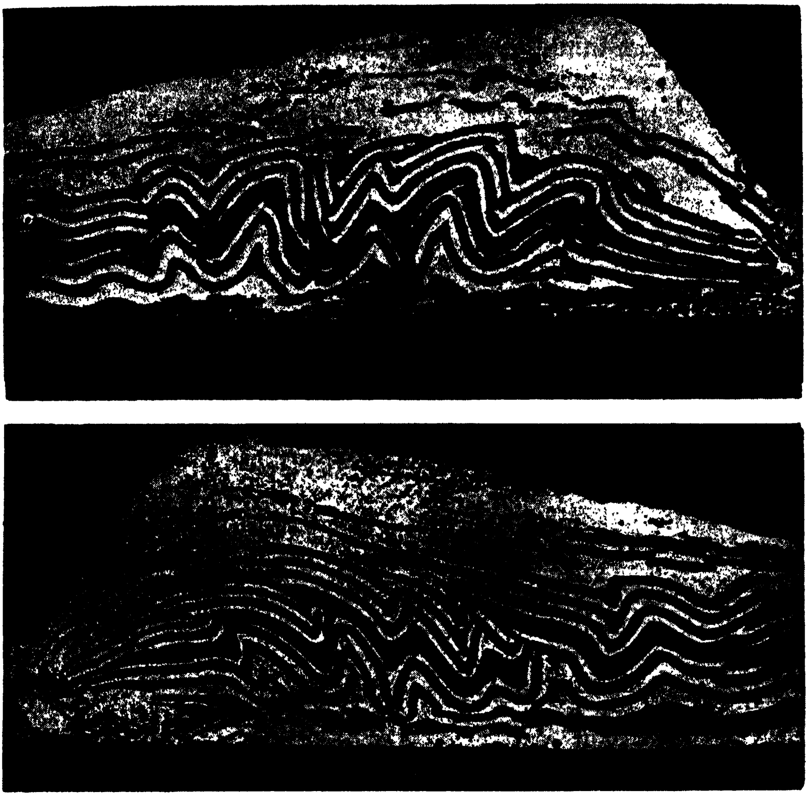


Fig. 91. Folds produced in one of Willis' experiments with the compression box. (B. Willis, 1890)

of the further downward continuation of the Westphalian folds was not considered by Böttcher. It is evident that the increase in intensity of folding with depth cannot continue downward indefinitely. In the analogous coal basin of Namur, in Belgium, a similar downward increase in the intensity and angularity of the folding is found in the coal measures. But the underlying Mississippian limestone shows again relatively simple folds.[21] The writer believes, therefore, that in the Westphalian coal region as in other analogous cases, the downward increase in the intensity of folding is the result of the struggle

[21] According to Fourmarier, quoted in S. von Bubnoff, *Geologie von Europa*, 2. Band, 1. Teil, Berlin, 1930, p. 299.

for space in relatively more plastic strata confined between the surface strata and a less yielding foundation.[22]

Stille's "Orogenes Zeitgesetz." The general question for which the Westphalian coal basin was considered in a measure a test case, was not whether any cases are known of sediments accumulated contemporaneously with folding. The question was whether the time consumed in folding is of the order of magnitude of that required to accumulate ten thousand feet of alternating marine and swamp sediments of the Pennsylvanian coal measures type and whether the slow continuous sinking of a geosyncline and typical orogenic folding have gone on contemporaneously anywhere. The result of the test is decidedly negative. So far the overwhelming evidence of all well known folded regions is in favor of a separate act of folding associated with more or less upward movement following a prolonged interval of downward movement and sedimentation.

Law 40 states that in some cases the time involved in the act of folding was quite short. Nothing is known to prove that an act of orogenic folding lasted longer than these cases for which more accurate timing is possible. On this ground Stille has taken the position that "all orogeny is confined to relatively few phases of short duration and of more or less world-wide importance."[23] This is his "orogenes Zeitgesetz." It expresses the exact opposite of continuous "mountain-folding."

In order to get a clear conception of the implications of Stille's thesis we must ask ourselves just what is meant by the expressions "orogeny" and "of short duration." Let us take up the second term first. Orogenic phases are short. How short? We must be specific if we wish to find a satisfactory basis for reasoning concerning the nature of orogenic deformation. Were these orogenic "spasms" of such short duration that they had catastrophal character causing widespread folding in an interval of but a few hundred or thousand years? Or were they epochs comparable in length to the glacial epochs of the Pleistocene, measured in tens of thousands of years? Or were they of

[22] This is, then, merely an illustration on a large scale of what Haug has called "disharmonic folding" (E. Haug, *Traité de Géologie,* Vol. I, 1911, p. 217). The result is often referred to as a "tectonic unconformity."

[23] H. Stille, *Grundfragen der vergleichenden Tektonik,* Berlin, 1924, p. 44. "Alle Gebirgsbildung ist an verhältnismässig wenige und zeitlich engbegrenzte Phasen von ± erdweiter Bedeutung gebunden."

the order of magnitude of the Pleistocene "period" itself, that is, measured in hundreds of thousands of years?

In general, when we want to understand the details of a geological process, especially when the measurement of time is involved, we can hope to find a sufficiently reliable record only in relatively recent events. In the most recent diastrophic movements the vertical displacements produced are much more conspicuous than deformations in the horizontal plane. The record of their progress is much more accessible and easier to read. The writer proposes, therefore, that for the moment we turn from typical orogenic deformation to the seemingly separate problem of the raising of a large welt above the present earth's surface. The reader who has followed the progress of reasoning so far will be prepared to find ultimately an intimate connection between vertical and horizontal deformations. What this connection is will be discussed in the second last chapter.

Adhering then, for the present, to the purely descriptive definition of crustal folds with which we began our reasoning (p. 13), we turn to two conspicuous modern welts to inquire into the distribution in time of the events that brought them into being—the Andes of Bolivia and Peru, and our own Sierra Nevada.

Central Andes. At two localities in the heart of the Bolivian Andes, plant fossils have been found in volcanic tuffs. One of these, southeast of Potosi in the Cordillera Real has been known for over half a century. The other lies near the western edge of the high plateau ("altiplanicie") of Bolivia, in the copper district of Corocoro. In 1919, Berry published an important analysis of the flora of these two localities and its bearing upon the age of uplift of the eastern Andes.[24]

The outcome of his analysis is this: The floras at the two localities, although widely separated geographically, are nearly identical. Most of the plants are forms of decidedly humid and tropical character and represent an assemblage very similar to that found today in eastern Bolivia and at other places in the Amazon basin. They are in striking contrast to the climate in which their remains are found today which is so dry that it permits "the growth of only drought-resisting grasses and low scrub."

[24] E. W. Berry, "Fossil Plants from Bolivia and Their Bearing upon the Age of Uplift of the Eastern Andes," *Proc. U.S. Nat. Mus.*, Vol. 54, 1919, pp. 103-64.

These fossil floras are found today over thirteen thousand feet above sea level. They must have grown at a much lower elevation. They prove, thus, in a rather unusual way that relatively recently this part of the Andes was raised thousands of feet, five thousand at least, if not twice as much.[25]

They are of interest to us chiefly, because they allow us to date the last great uplift of that part of the Andes. Berry's analysis of the flora shows conclusively that it is of late Tertiary, probably Pliocene rather than late Miocene age.

Barrell's cautious estimates of time contained in his classical paper on "Rhythms and the Measurements of Geologic Time" assign 1,000,000 to 1,500,000 years to the Pleistocene and 6,000,000 to 7,500,000 years to the Pliocene.[26] This, then, is the order of magnitude of the interval within which this uplift took place. But was it continuous throughout this time?

For the last stages of the history of this uplift we can obtain a definite answer from a study of the topographic forms. Bowman has given a lucid description[27] of the southern Andes of Peru based not only on extended field observations, but also on a group of detailed topographic maps the preparation of which constituted the chief object of the Yale Peruvian Expedition of 1911.[28]

Throughout the central Andes,[29] the topography of the uplands

[25] With the fossil leaves an inarticulate brachiopod was found in shales that seemed to be part of the plant-bearing tuff series. It was thought to be a species of *Discinisca* and as such was taken to indicate that the fossil flora grew at sea level. On a later visit, Drs. Berry and Singewald found that the shale underlies the tuff series unconformably and carries Ordovician trilobites. The brachiopod seems to be an *Orbiculoidea*. (Personal communications from Drs. E. W. Berry and J. T. Singewald, Jr.)

[26] J. Barrell, "Rhythms and the Measurements of Geologic Time," *Bull. Geol. Soc. America*, Vol. 28, 1917, p. 884. Compare with this the figures in Arthur Holmes, "Radioactivity and Geological Time," *Nat. Research Council, Bull. 80*, 1931, pp. 435-9.

[27] I. Bowman, *The Andes of Southern Peru*, New York, 1916.

[28] For an account of the difficulties under which the topographer of the expedition, Kai Hendriksen, carried through his task of plane-tabling over a distance of two hundred miles, see Appendix A of Bowman's book (pp. 315-20). All the maps are contained in the book. The section of the Andes covered by these maps lies about three hundred miles to the northwest of Corocoro.

[29] See also D. H. McLaughlin, "Geology and Physiography of the Peruvian Cordillera, Department of Junin and Lima," *Bull. Geol. Soc. America*, Vol. 35, 1924, pp. 591-632, esp. pp. 623-7.

stands in strong contrast to that of the lower slopes of the valleys. The upland has the character of a "mature" mountain region with well graded, relatively gentle slopes and rounded contours. "Upon the softer rocks at the lowest levels near the largest streams the surface was worn down to extremely moderate slopes with a local relief of not more than several hundred feet. Conversely, there are quite unreduced portions whose irregularities have mountainous proportions, and between these extremes are almost all possible variations."[80] Parts of the wide floors of the main valleys of this older upland topography form conspicuous shoulders along the major streams.

Into this older topography of the upland, the deeper portions of the valleys are cut. They have precipitous slopes, often in the form of inaccessible cliffs, while cliffs are unknown on the rounded topography of the upland except for glacier-cut slopes.

From the exact topographic maps at his disposal, Bowman constructed accurate cross-profiles of the valleys on the high plateau. From them longitudinal profiles of the old valley floors were obtained. They show the regularity and low angles characteristic of well graded streams.[81] Such gentle stream profiles point as definitely to a prolonged absence of upward crustal movements as the mild contours of the topography above them.

When these profiles are extended toward the margin of the mountain belt, they are found to lie nearly a mile above the level of the sea. "The streams are now sunk from one to three thousand feet below their former level. Even in the case of three thousand feet of erosion the stream profiles are still ungraded, the streams themselves are almost torrential, and from one thousand to three thousand feet of vertical cutting must still be accomplished before the profiles will be as gentle and regular as those of the preceding cycle of erosion, in which were formed the mature slopes now lying high above the valley floors."[82]

In the departments Junin and Lima of Peru, some four hundred miles farther to the northwest, McLaughlin recognized a further complication in this uplift. There, as in the region studied by Bowman, only local remnants are left of the old "broad valleys with flat gra-

[80] I. Bowman, *op. cit.*, p. 188.
[81] *ibid.*, pp. 188-92, esp. Fig. 128, p. 191.
[82] *ibid.*, p. 231.

dients and gentle side slopes." The uplift with which we are here concerned has caused the rejuvenated streams to cut deep valleys. Where these valleys are cut in resistant rock, they have the shape of single canyons just like those described by Bowman. In less resistant rocks, however, a shoulder with gentler slopes runs some one thousand to two thousand feet below the level of the old upland valleys, forming benches on which hill villages have developed in many localities. "These slopes, now midway in the great canyons, are extensively terraced and cultivated in numerous farms called 'chacras.' "[33]

The great rejuvenation, then, must have taken place in two steps. After the first uplift, enough time elapsed to allow the slopes in less resistant rocks to become relatively gentle. On quite soft Tertiary rocks, lateral erosion even developed "wide valleys with gentle slopes, which now stand in marked contrast to the more recent final gorge."[33] This "chacras" stage, as McLaughlin calls it, must have been considerably longer than the time elapsed since the last uplift, the "canyon stage," which extends to the present.

Throughout the regions studied by McLaughlin and Bowman, the effects of glaciation are seen to have been superimposed on the topography created by the uplift which initiated the canyon cycle. In the upper reaches, glacial scouring and frost action modified the preglacial topography in familiar fashion. Farther down in the valleys lie the corresponding moraines and the glacial outwash hundreds of feet thick, now undergoing erosion. Their presence shows that the canyon had been essentially completed before the advent of the later stages of glaciation, at least.

The topographic forms show clearly, then, that the uplift took place in definite steps, separated by times of crustal rest. The first uplift, which initiated the "chacras" stage, ended a long period of rest during which the mountains assumed subdued forms along the high axis and forms approaching old age on lower and less resistant terranes. The "chacras" stage itself must have consisted of an uplift, followed by a time of rest, during which the newly deepened valleys could be widened at least on less resistant rocks. The second, greater uplift, which introduced the canyon stage, must have practically come to an end around the middle of Pleistocene time.

[33] D. H. McLaughlin, *op. cit.*, p. 625.

The relative amount of erosion accomplished in the last two stages gives us a means of fitting the two uplifts roughly into the geological time scale. The last and greatest uplift must have occurred at or near the end of Pliocene time. If we accept Barrell's figures, it must have occurred something like one million years ago. The earlier uplift, then, must lie several times as many years farther back. This places it in the earlier part of the Pliocene if not at the end of the Miocene.

In each case, the time consumed in the actual process of uplifting must have been of a lower order of magnitude, measured by hundreds of thousands of years rather than by millions of years. Let us see how these figures agree with the results obtained in another, even more carefully studied, region.

The Sierra Nevada, California. The classical study of the "geologic history of the Yosemite valley," recently published by Matthes,[34] like Bowman's study of the Andes, contains quantitative profile studies made possible by the detailed mapping of the region.[35] The story told is remarkably like that of the Andes of Peru and Bolivia. As far as it concerns us here, the story begins with a long period of quiet during which the gently southwestward sloping surface of what is now the Sierra Nevada was reduced to the rounded contours of subdued mountains along its axis with post-mature topography of less and less relief on the lower slopes. The rivers, such as the Merced, Tuolumne, and San Joaquin Rivers, flowed in very broad, shallow valleys, last remnants of which still exist as upper shoulders along the sides of the deep valleys in which these streams now flow. Where lava flows buried these early valleys, forcing the streams into new channels, fossils found in the lava-covered alluvium are found to be of later Miocene age.[36] Careful analysis of reconstructed stream profiles shows that at that time that portion of Merced River valley which later became the Yosemite, stood only about 800 feet above sea level, while Mt. Lyell, in the High Sierras, may have been as high as 4,000 feet.[37] Matthes calls this early stage of topographic development the

[34] F. E. Matthes, "Geologic History of the Yosemite Valley," *U. S. Geol. Survey, Prof. Paper 160*, 1930.

[35] In this case, Dr. Matthes himself was the topographer.

[36] e.g., impressions of leaves and a tooth of an extinct species of horse, from Table Mountain in Tuolumne County, identified by R. W. Chaney and Chester Stock. F. E. Matthes, *op. cit.*, p. 28.

[37] F. E. Matthes, *op. cit.*, p. 44.

"broad-valley stage." In the diagram, Fig. 92,[38] which shows the pre-glacial shaping of Yosemite valley drawn to scale, the broad-valley stage is represented by *A*.

The transformation from the broad-valley stage to the final condition (aside from the effects of glaciation) was accomplished by two uplifts. The first seems to have lifted the floor of Merced River Valley from 800 feet to 1,800 feet, and carried Mt. Lyell from about 4,000 feet to something like 7,000 feet above sea level. There followed an episode of rest long enough for such rivers as Merced River to widen their valleys into very broad flood plains on the less resistant sedimentary rocks of the lower slopes of the Sierra Nevada, while higher up, in the granitic uplands, the second valley remained relatively narrow and steepsided. Matthes calls this the mountain-valley stage (see Fig. 92). The period of rest in which large stretches of the valleys were widened out, seems to have comprised most of Pliocene time.

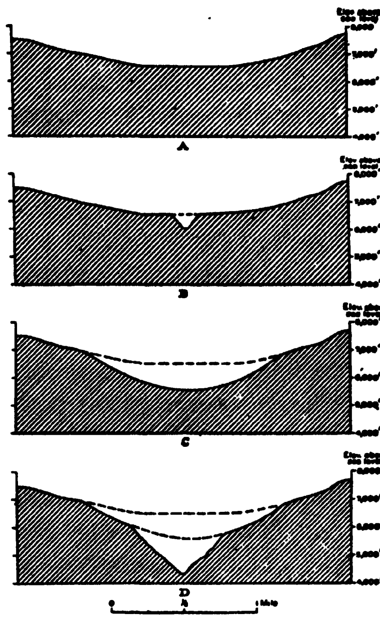


Fig. 92. Cross-sections illustrating the successive stages in the cutting of Merced Canyon which now forms Yosemite Valley, California.

The sections are drawn to scale and show the general proportions of that part of the canyon which ultimately became the Yosemite Valley. *A* = broad-valley stage, presumably of late Miocene time; *B* = inner gorge cut after first strong tilting of Sierra Nevada block; *C* = mountain-valley stage, presumably of late Pliocene time; *D* = canyon stage, produced early in Pleistocene time by the last great Sierra uplift.

(F. E. Matthes, 1930)

The greatest upward movement began at or near the end of Pliocene time. The floor of that part of Merced River valley which was to be the Yosemite was lifted to twice its former height, to near 4,000 feet above sea level, and Mt. Lyell in the High Sierras was raised

[38] Reproduced from F. E. Matthes, *op. cit.*, Fig. 4, p. 32.

above 13,000 feet. The rejuvenation of stream work which followed caused deep canyons to be cut. This is Matthes' "canyon stage." It was practically completed before glaciation assumed any proportions in the Sierra Nevada. The transformation of the upper and middle courses of the Sierra canyons into the bold features which we now see in the Yosemite of Merced River and similar stretches in other valleys of the Sierra Nevada[39] is the work of Pleistocene glaciation. The work of two epochs of glaciation, separated by a relatively long interval of time, is still well recorded by moraines and other distinctive features. There are suggestions of one, possibly two, still older glacial epochs.[40]

The three-story cross-section of the valleys in the central part of the Sierra Nevada, then, tells the same story that Bowman and McLaughlin read from the topographic forms of the central Andes. A long period of orogenic quiet extending through the greater part of the Miocene period, the broad-valley stage, ended by a first uplift, vaguely dated near the end of Miocene time. The extent to which the lower portions of the larger valleys were widened in the interval between the first and the second uplift, that is, in the mountain-valley stage, leads to two important conclusions: (1) The mountain-valley stage comprised much more time than the canyon stage. (2) The time involved in the actual upward movement during the first uplift, must have been a relatively small fraction of the whole mountain-valley stage.

The first of these conclusions places the time of the second uplift near the end of the Pliocene. By way of rough estimate, Matthes adopts Barrell's figures, six million years for the Pliocene mountain-valley stage and one million years for the canyon stage.

Since there is no evidence of important upward movements during the last part of the glacial history of the Sierra, the duration of the last upward movement must be measured by hundreds of thousands of years at most. A similar duration is indicated for the first uplift

[39] Such as the Tuolomne (Hetch Hetchy Valley), Middle Fork of Kings River (Tehipite Valley), South Fork of Kings River (Kings River Canyon). F. E. Matthes, *op. cit.*, p. 8.

[40] F. E. Matthes, *op. cit.*, pp. 61-75. See also E. Blackwelder, "Evidence of a Third Glacial Epoch in the Sierra Nevada," *Bull. Geol. Soc. America*, Vol. 39, 1928, p. 268; *idem*, "Glacial History of the East Side of the Sierra Nevada," *ibid.*, Vol. 40, 1929, p. 127.

when its effect is compared with the widening that followed it. The evidence and the reasoning employed are, thus, the same as in the case of the Andes, and the numerical results are identical.

Coast Ranges of California. In the Coast Ranges of California, immediately to the west of the Sierra Nevada, vertical movements occurred on a large scale in the same time interval, that is, from near the close of the Pliocene to the middle of Pleistocene time. But here they were accompanied by much intense folding and thrust faulting. Here, then, the disturbance was "orogenic" in the strictest sense of the word. This epoch of folding, in fact, produced far more structural changes than any earlier orogenic epochs since the end of the Jurassic, so that it is spoken of as the "Coast Range revolution." Since beds of Lower Pleistocene age are often found highly folded and faulted, most of the movement must have taken place in Pleistocene time.[41] It is well known that the compressive stresses are still active. But the result of the last half of Pleistocene time does not compare with that achieved in the first half.

Here, then, we have a means of measuring an orogenic epoch in the strict sense of the word in terms of years. And we arrive at the same figure obtained for the essentially vertical movements in the Andes and in the Sierra Nevada. The main deformation was produced in an interval of time measured by hundreds of thousands of years rather than by millions or tens of thousands of years.

Conclusion. The convergence of evidence from the independent study of two widely separated regions of dominantly vertical uplift and one of intensive horizontal deformation points to a simple multiple of one hundred thousand years as the duration of the episodes of orogenic disturbances in the broad sense of the word. The writer assumes that this has been the order of magnitude of orogenic episodes in general. His reasons for making this assumption are these: (1) As nearly as can be told at present, the last of the episodes of vertical uplift, that of early Pleistocene time, coincides in time with typical orogenic movements in California and in other regions, as may be seen from Table VI opposite page 413. (2) The order of magnitude found for it, at most 1/30 or 1/40 of the length of a typical geological period, agrees with that indicated by the strati-

[41] Bruce L. Clark, "Tectonics of the Coast Ranges of Middle California," *Bull. Geol. Soc. America*, Vol. 41, 1930, p. 794.

graphic evidence of all times in all regions of true orogenic deformation. (3) There is reason to believe that vertical movements are the outcome of the same ultimate forces which cause horizontal deformation and should, therefore, be expected to be of similar duration.

The last point will be taken up in the next chapter. Those readers who object to correlating the two types of deformation in time should defer judgment until the evidence of the last chapter has been read. Such readers, in general, would class the dominantly vertical movements of the last stages in the orogeny of the Sierra Nevada and the Andes as "epeirogenic," in contrast to "orogenic" movements.

This brings up in concrete form the other element of uncertainty in Stille's "Orogenes Zeitgesetz." What phases of diastrophism should be included in the term "orogenesis"? Is the broad sense in which the term "orogenic" was used above, justified or not?

Orogenesis versus Epeirogenesis. When we go back to Gilbert's original definition of these terms, we find that there can be no doubt about their use. He wrote: "Having occasion to contrast the phenomena of the narrower geographic waves with those of the broader swells, I shall take the liberty to apply to the broader movements the adjective *epeirogenic*, founding the term on the Greek word ἤπειρος, a continent. The process of mountain formation is *orogeny*, the process of continent formation is *epeirogeny*, and the two collectively are diastrophism. It may be that orogenic and epeirogenic forces and processes are one, but so long at least as both are unknown it is convenient to consider them separately."[42]

Confusion concerning the use of the two terms resulted when the study of the tectonics of mountains was separated from that of their physiography, each being cultivated by different groups of men. The result is that the structural geologists have developed their own definition of "orogeny" based exclusively on criteria observable in the stratigraphic and structural record of the past. Stille has given the clearest statement of this "structural" concept of the terms orogenesis and epeirogenesis. He defines them as follows:

Orogenic processes produce structural changes visible to the eye, such as faults, folds, thrusts, and are of short duration ("episodic");

[42] G. K. Gilbert, "Lake Bonneville," *U.S. Geol. Survey*, Mon. I, 1890, p. 340.

Epeirogenic processes do not produce structural changes other than broad warping evident only from regional stratigraphic studies and are of seçular duration.[48]

Stille excludes specifically from the orogenic class what he calls the "*en bloc* movements" which affect folded mountains, generally after a prolonged period of crustal rest and erosion. They are the movements to which most modern mountain belts owe their present topographic form. The Rocky Mountains with their uplifted peneplains are among the examples quoted by Stille. The uplift by which they come to be is called epeirogenic because it was thought not to have been of short duration ("langandauernd") and not to have produced structural changes.

Can we call the last uplift which transformed the central Andes from a mature to post-mature mountain land into the precipitous chains it now shows, "langandauernd"? The writer's attempt to obtain some conception of the absolute length of time involved in that process was undertaken to good purpose. Have we any concrete reason to assume that the repeated episodes of folding which gave the folded Appalachians their structure took place in an interval of time shorter by a different order of magnitude? If not, the length of time involved in the process should not be made a criterion to distinguish "orogenic" from "epeirogenic" movements.

The real core of Stille's definition refers to that property which alone can be observed impartially in the field, the effect of the disturbance on the visible structure of the rocks. There is a real difference between a disturbance which produces a belt of folds like that of the Appalachians and one which produces the vague warpings which we recognize in ever-increasing complexity from the innumerable shiftings of sediments and gaps in the stratigraphic series due to times of non-deposition. But the difference is adequately described by the terms "thrusting," "faulting," "folding," and "warping." In the one case the horizontal displacement dominates the results, in the other the vertical. Are we really gaining anything fundamental by calling the former "orogenic" and the latter "epeirogenic"? The very way we speak of one kind of deformation "dominating" suggests the possibility that the two are due to two compo-

[48] *op. cit.*, p. 11.

nents of one and the same fundamental process. That possibility is worth considering.

Let us look at what is known of the diastrophic history of the central Andes. During the late Cretaceous and again in the early Tertiary there were at least two epochs which left a record of folding and faulting in the central Andes.[44] Especially the latter of these movements created a mountainous relief.

The next diastrophic movement was the one which carried the tuffs of Potosi to mountainous heights. Its structural effect has been small but distinct. The Pliocene deposits show frequently small, but recognizable dips and even gentle folding. More important still, at Potosi the uplifted tuffs were intruded by an ore-bearing dacite. Some of the granodiorites of the Andes of Bolivia and Peru may be of similar late date. Yet the sum total of structural changes was small. The amount of uplift, on the other hand, was large. The total vertical displacement may have been achieved in several stages.[45] It produced the mountains which subsequently were reduced to the mature or postmature topography of the Andean uplands. Steinmann speaks of this as the last recognizable epoch of folding (the "Quichuanian" epoch of folding). After a long interval came the last uplift. Of the total elevation of 13,500 feet of the beds at Potosi, as much as 5,000 feet may have been gained in this last stage. Since the central Andes had stood already high enough to be undergoing active erosion everywhere, no sediments existed by which to recognize such differential movements as would give rise to gentle tilting and folding. But this does not mean that the uplift deserves being called *en bloc*. Detailed studies in other mountain regions, such as the San Juan Mountains, the Alps, and the Appalachians have shown that in such movements the old land surfaces undergo well defined deformations. They are by no means lifted up *en bloc*.

The history of the Andes, then, like that of any folded mountain system, leads from relatively small uplift with much folding to large uplift with little folding. But all the while both kinds of deformation have produced large effects only in that narrow belt on the earth's surface which at present stands up so boldly. That they have been

[44] The "Peruvian" and "Incan" epochs of G. Steinmann, *Geologie von Peru*, Heidelberg, 1929, pp. 288-90.

[45] See D. H. McLaughlin, *op. cit.*, pp. 624-5.

so limited seems to the writer to be the truly significant fact. By applying the term "orogenic" to all deformation which produces excessive changes in linear elements of the earth's crust, the "mobile belts," we combine the essentials of both the physiographic and the tectonic definitions. This we did in the first chapter of this book where we defined "excessive" as meaning in excess of the dimensions realized by similar movements outside of mobile belts.

If we adopt this definition we can put the result of the preceding discussion into the following form.

Opinion 31. At any point on the earth, positive, that is, upward orogenic movements are limited to relatively short epochs separated by much longer epochs of rest or of negative movement. The duration of such an orogenic epoch is measured in terms of hundreds of thousands of years and is of the same order of magnitude whether the horizontal or the vertical component of movement dominates in the visible results of the deformation.

2. Synchroneity of Orogenic Movements

If we accept the last conclusions we face the larger problem of the synchroneity of orogenic movements. Are any cases known in which orogenic deformation occurred simultaneously in different parts of the earth?

Post-Franciscan folding in California. Let us examine two cases in which the structural conditions observed in the field are such that the time limits within which folding took place can be narrowed down sufficiently. On pages 385-7 the statement was made that in the California Coast Ranges orogenic movements occurred in latest Jurassic time, before and possibly also after Portlandian time.

In Europe we find the same point in the stratigraphic column marked by widespread orogenic movements. In southeastern Europe they are conspicuous in the Crimea and in the Caucasus and have been recognized in the Balkan peninsula and in the Apennines.[46] In these regions the Portlandian formations, which in the Mediterranean region bear the name Tithonian, transgress across folded pre-Tithonian Jurassic and older sediments.[47]

[46] H. Stille, *Grundfragen der vergleichenden Tektonik,* Berlin, 1924, pp. 138-9.
[47] E. Haug, *Traité de Géologie,* Vol. II, 1908-1911, p. 1076.

In northern Germany, this was the time of chief deformation in the Saxonian orogenic belt. Here much detailed stratigraphic and structural work has shown that three separate phases of deformation can be distinguished. According to Dahlgrün they occurred at the following points in the stratigraphic sequence:[48]

	Hauterivian
	Upper Valanginian
	3rd phase
	Wealden (freshwater)
Portlandian	Serpulite *2nd phase* Marls of Münd Eimbeckhausen limestone Gigas beds
	1st phase
	Kimmeridgian

The first phase seems to have been the most important. The coincidence in time of the main phases in pre-Portlandian time and of the minor phases at the end of Portlandian time in northern Germany and in the Coast Ranges of California is as close as we can hope to establish at the present time for two widely separated regions.

"Laramide" folding in Colorado and Wyoming. The "Laramide revolution" may serve as a second illustration. In Wyoming and Colorado two orogenic phases have been pronounced enough to have left a conspicuous record. In order to visualize the stratigraphic setting of this record, study the correlation chart here reproduced in Table V from a paper by Thom and Dobbin.[49] This table shows the transition beds between the typical Cretaceous and the typical Eocene formations on both sides of the Bighorn Mountains, especially to the east and northeast in Wyoming and Montana and out into the Dakotas, and on the east side of the Front Range in Colorado, in

[48] Quoted from Stille, *op. cit.*, pp. 140-1. (F. Dahlgrün, "Tektonische insbes. kimmerische Vorgänge im mittleren Leinegebiet," *Jahrb. Preuss. Geol. Landesanstalt*, 1921, Vol. 42, p. 723.)

[49] Reproduced from W. T. Thom and C. E. Dobbin, "Stratigraphy of Cretaceous-Eocene Transition Beds in Eastern Montana and the Dakotas," *Bull. Geol. Soc. America*, Vol. 35, 1924, p. 498, Table 2.

the Denver basin. The Pierre and type Fox Hills formations and the Cannonball member of the Lance formation are normal marine sediments. All others are brackish water deposits with coal beds or alluvial deposits with freshwater molluscs, leaves of land plants and remains of vertebrates.

At three points in this diagram definite unconformities are indicated. The first lies at the base of the Colgate sandstone member of the Fox Hills (as defined by the authors) in eastern and central Montana. This is thought to be the same unconformity that is seen at the base of the Arapahoe foramtion in the Denver basin.

The second unconformity is found below the Lebo member of the Fort Union formation in Montana. It corresponds to that which occurs locally in various parts of Wyoming at the base of the Fort Union.[50]

The third unconformity lies at the base of the Wasatch formation. It is the most important of the three.

Only two of these unconformities are marked by thick conglomerate fans, each deriving its coarse sediments from a relatively abrupt uplift along one of the mountain axes, each overlapping mountainward as the accumulation of sediments proceeded. The first of these is recorded in the Denver basin where the conglomerates, especially the basal conglomerate of the Arapahoe formation, contain recognizable fragments of most of the underlying formations from the Laramie to the crystalline rocks of the Mountain axis.[51] The Arapahoe and the Denver formations carry the "Triceratops fauna" which is characteristic of the Lance of Wyoming and the Hell Creek beds of Montana.

In Wyoming and Montana there is no clear sedimentary record of this first orogenic movement. There, a second strong orogenic movement is indicated by the thick Kingsbury conglomerate[52] which forms

[50] As, for instance, on the Absaroka-Owl Creek Mountain front and in the border belt of the Bighorn basin, according to D. F. Hewett, "Geology and Oil and Coal Resources of the Oregon Basin, Meeteetse, and Grass Creek Basin Quadrangles, Wyoming," *U.S. Geol. Survey, Prof. Paper 145*, 1926, esp. table on p. 70.

[51] G. H. Eldridge in "Geology of the Denver Basin in Colorado," *U.S. Geol. Survey*, Mon. 27, 1896, pp. 152-3.

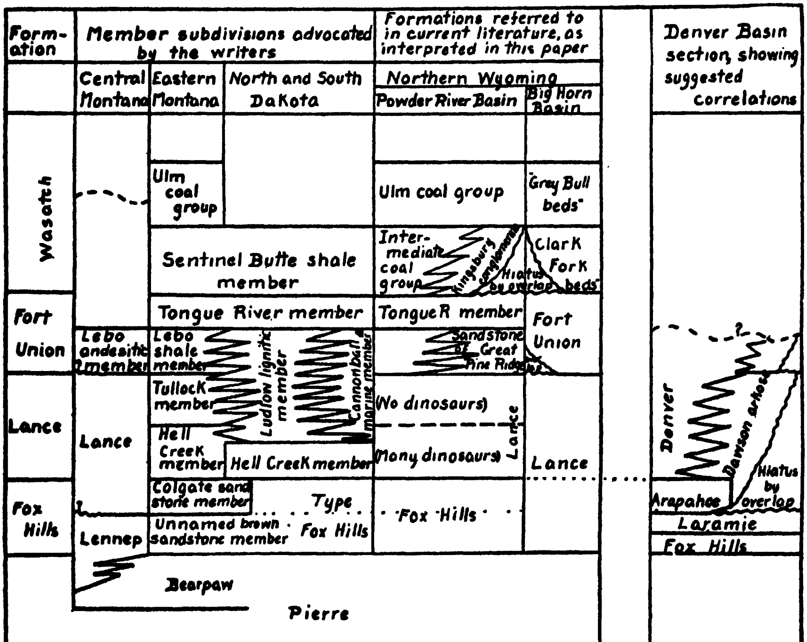
[52] N. H. Darton, "Geology of the Bighorn Mountains," *U.S. Geol. Survey, Prof. Paper 51*, 1906, p. 61; C. H. Wegemann, "Wasatch Fossils in So-called Fort Union Beds of the Powder River Basin, Wyoming," *ibid., Prof. Paper 108*, 1918, pp. 59-60.

local coarse alluvial fans interfingering with the lower Wasatch beds on the east side of the Bighorn Mountains. Here again pebbles of the earlier formations can be recognized, such as Mississippian limestones with crinoids and spirifers, characteristic flat pebbles of the Cambrian Deadwood formation, and coarse-grained granites of the mountain core.[53] The formation overlaps mountainward.[54]

TABLE V

Cretaceous-Tertiary Transition Beds

(W. T. Thom and C. E. Dobbin, 1924)



When we look at the faunal character of the transgressive formation which spread after the mountain folding, we find a peculiar condition. The fauna of the chief body of the Wasatch differs from the older formations in a profound way. In it appear for the first time the representatives of the dominantly modern orders of mammals

[53] H. S. Gale and C. H. Wegemann, "The Buffalo Coal Field, Wyoming," *U.S. Geol. Survey, Bull. 381*, p. 144.

[54] *Geologic Map of Wyoming*, 1:500,000, U.S. Geol. Survey, 1925.

among which *Eohippus* (= *Hyracotherium*) is the most celebrated form. But this fauna does not extend down to the base of the transgressive series. The basal beds carry a mammal fauna in which the modern element is almost wholly lacking. It is made up largely of archaic forms related to those of the preceding formations. These are the sub-Wasatch or Clark Fork beds[55] of the Bighorn basin (see Table V). They occur in precisely the same relation to the preceding rocks in the San Juan basin, where they are known as the Tiffany beds.

In terms of vertebrate faunas, the formations represented in Table V form three groups: A lower one of undoubted Cretaceous age, ending with the Fox Hills-Laramie beds. One in the middle, representing the Transition beds, the Lance and Fort Union formations, classed as Paleocene. On top, the Wasatch is of undoubted Eocene age. The first important orogenic movement occurred at or very near the beginning of the Paleocene vertebrate fauna. The third took place shortly, but definitely, before the relatively sudden appearance of the Wasatch fauna.

Between the deposition of typical Cretaceous and typical Eocene sediments, important orogenic movements took place in many parts of the world. In South America a major phase of the folding of the Andes falls into that time interval. More or less important movements are indicated at many points in the Alpine system from Spain to Sumatra.[56] Generally, however, the interval is not represented by transition sediments so that a more exact comparison with the phases in the Rocky Mountains is not possible. In northern Europe, where such sediments are present, no large orogenic movements took place, but broad folding associated with minor faulting affected northern France and adjoining parts of Belgium. This folding is part of a sequence of folding movements which were described by Bertrand.[57] He placed the beginning of this folding after the Maastrichian and before the Danian formations. In the region of Mono, in Belgium, minor faulting associated with this disturbance occurred twice. Ac-

[55] W. D. Matthew, "Fossil Vertebrates and the Cretaceous-Tertiary problem," *Am. Jour. Sci.*, Vol. 2, 1921, p. 219.

[56] H. Stille, *Grundfragen der vergleichenden Tektonik*, Berlin, 1924, pp. 156-63.

[57] M. Bertrand, "Sur la continuité du phénomène de plissement dans le bassin de Paris," *Bull. Soc. Géol. France*, 3e ser., Vol. 20, 1892.

cording to Cornet,[58] the two epochs of deformation lie in the stratigraphic sequence as follows:

Upper Landenian (freshwater) (= Sparnacian)
Lower Landenian (marine)

2nd disturbance

Upper Montian (freshwater)
Lower Montian (marine and brackish)
Danian (marine)

1st disturbance

Maastrichian (marine)

The Maastrichian is of undoubted Cretaceous age. The Danian is the first of the transition beds of disputed position in the traditional systems. In strata of Danian age, the only European Ceratopsid dinosaur was found.[59] In this as in the ambiguous relations of its invertebrate fauna, it resembles the Lance formation. The Montian represents the typical development of the Paleocene in this region. Above it, and below the transgressing lower Landenian, sands are found locally known as Heersian. These carry at Gelinden a flora which among European floras is nearest related to that of our Fort Union beds. The lower Landenian is still distinctly transitional, that is, Paleocene. The upper Landenian, on the other hand, is the equivalent of the Sparnacian formation of the standard European scale. It carries a typical Wasatch fauna. It represents the first typical Eocene of Europe. Scott goes so far as to say that "at no subsequent time were the mammalian faunas of North America and Europe so nearly identical as during the Wasatch-Sparnacian age."[60] The comparison with American stratigraphy is made complete by the presence, locally, of a vertebrate fauna immediately below the Sparnacian which corresponds closely to that of our Clark Fork beds (the Cernaysian).[61]

These correlations enable us to compare the mild orogenic movements of northern France and western Belgium with the phases of our "Laramide revolution." In both regions the first movement

[58] I. Cornet, *Géologie*, Vol. I, Mono, 1909. Quoted from Stille, *op. cit.*, p. 160, the original not being available to the writer.

[59] E. Haug, *Traité de Géologie*, Vol. II, 1908-1911, p. 1414.

[60] W. B. Scott, *A History of Land Mammals in the Western Hemisphere*, New York, 1913, p. 108.

[61] W. D. Matthew, *op. cit.*, p. 220.

occurred before the dinosaurs had become extinct. A later movement took place in the latter part of the transitional epoch, but decidedly before the rather abrupt appearance of the Wasatch-Sparnacian vertebrates. The two movements seem to have taken place as nearly simultaneously as we may hope to prove anything by stratigraphic correlation from one continent to another.[62]

Law and general comment. The two examples quoted above may be duplicated for other periods and in different parts of the world. The writer believes them to be sufficiently typical to permit us to generalize and derive from them the following law.

Law 41. Orogenic movements have frequently taken place simultaneously in widely different parts of the world.

Taken by itself, this law means little enough. If it could be proved that orogenic movements occupied large fractions of the periods in which they occurred and that deformation was under way at one or several points on the earth at every moment of geological time, it would not be revealing to find here and there definite evidence that in two or more regions orogenic deformation proceeded simultaneously. The law would express an irrelevant truism.

The recognition of the episodic character of the orogenic movement is, therefore, really basic for this discussion. The examples given above were chosen particularly to supplement the material given to illustrate the basis for this concept. In each of these cases, wherever sufficient data are available, it is clear that the time involved in one orogenic episode was a small fraction of one period.

Shepard has tried to demonstrate that "geological evidence shows a series of diastrophic movements which are almost continuous from the Ordovician to the present."[63] The evidence is presented in the form of a table. In it we find, for instance, orogenic movements recorded for the "Beginning of Devonian"; "Lower or mid-Devonian"; "Late Devonian"; "End of Devonian." At first sight this suggests "continuous" orogenesis. It looks convincing, however, only when the short, episodic duration of orogenic movements is denied.

[62] The least pronounced of the three movements recorded in Wyoming and Montana does not seem to have been recognized in northern Europe.

[63] F. P. Shepard, "To Question the Theory of Periodic Diastrophism," *Jour. Geol.,* Vol. 31, 1923, p. 613.

This Shepard does explicitly. He writes:[64] "The time of diastrophism was supposed not to be a point of time, but to have extended over a considerable fraction of a period, let us say on the average about a third of a period. This may sound arbitrary, since the length of periods varies, but probably no harm was done in making such an assumption, because it is becoming well recognized that orogeny is not as brief a process as it was formerly considered."

The discussion on the preceding pages of this book shows that this statement is not acceptable without careful proof. If it is incorrect, that is, if orogenic movements occurred in brief episodes between longer periods of rest, the existence of but four epochs of deformation during the whole Devonian period[65] is excellent evidence that orogenic deformation was not continuous.

Blackwelder and Stille's lists of orogenic epochs. One year after Shepard's paper Stille published his *Grundfragen der vergleichenden Tektonik* (1924). In this masterly contribution to critical geological thinking a wealth of material is assembled bearing on the question of the world-wide synchronism of orogenic movements. Although he sought as high precision in the stratigraphic timing as possible, Stille succeeded in assigning to a relatively small number of epochs practically all the numerous individual orogenic movements recorded from all parts of the earth. To the writer this seems significant. If orogenic movements had been under way somewhere on the earth at all times since the beginning of the Paleozoic, the difficulties of correlating the records of orogenic movements should multiply as the number of cases considered and the accuracy of stratigraphic timing increase. When we compare the earlier tables of correlation of orogenic epochs published by R. T. Chamberlin[66] and by Blackwelder[67] with those of Stille's, we find an increase in the number of epochs

[64] *op. cit.*, p. 602.

[65] Some of Shepard's time assignments are of doubtful value as he himself indicates in the text. For the Alaskan folding, for instance, which he calls "Lower or mid-Devonian," the stratigraphic limits as given in the source quoted are far too vague to justify the narrow limits given by Shepard. The assignment of the Crimean folding to the mid-Jurassic does not follow from the words of the source to which reference is made.

[66] R. T. Chamberlin, "Periodicity of Paleozoic Orogenic Movements," *Jour. Geol.* Vol. 22, 1914, pp. 315-45.

[67] Eliot Blackwelder, "A Summary of the Orogenic Epochs in the Geologic History of North America," *Jour. Geol.*, Vol. 22, 1914, pp. 633-54.

distinguished, but no corresponding embarrassment about correlating the more numerous records in spite of much greater attention to stratigraphic detail.

From this the writer concludes that at least the more important orogenic epochs were felt essentially simultaneously in all parts of the globe. Any one of them may have produced recognizable structural results in only a few widely separated regions. But if this view is correct, all deformations produced by one orogenic epoch should appear registered at or very near the same point in the general stratigraphic time scale. The present crude state of knowledge concerning long-distance correlations and the almost complete lack of sufficiently detailed stratigraphic and structural work in most orogenic belts make it impossible to test this view more accurately at the present.

R. T. Chamberlin merely speaks of "Ordovicides," "Silurides," "Devonides," "Culmides," "Westphalo-Carbonides," "Permo-Carbonides," designating by these terms the sum total of folding which took place "either at or near the close of" the respective periods. Blackwelder distinguished ten post-Lipalian epochs of folding and assigned to them tentative places in the stratigraphic column, subdividing periods merely by the words "Lower," "Middle," and "Upper." In his book, Stille names twenty post-Algonkian orogenic epochs, of which six consist of two or three separate phases, and mentions as doubtful four more. In Table VI the writer has tabulated the epochs recognized by Stille. This list represents a landmark in the study of the time-relations of orogenic epochs. It is, of course, still incomplete. A number of additional epochs are indicated by detailed studies in many parts of the world. But it forms an important stepping-stone in the building up of a comprehensive knowledge of orogenic movements.

In the table, arrows mark the intervals in which orogenic epochs occurred. The numbers and names attached to them are Stille's. The more or less equivalent names in use for North American orogenic epochs are given in parentheses. In the columns on the right a few regions in Europe and North America are listed in which the record of these orogenies is well recognized.

Discussion of Stille's table of orogenic epochs. The large number of orogenic phases is the outstanding feature of this table. The largest number, one-third of the total, is recorded for post-Cretaceous time.

We have no reason to think that this crowding toward the present corresponds to any real difference between the Cenozoic and the earlier part of geologic history. We know that Stille's table is incomplete even as far as now available information goes, and accurate stratigraphic and structural knowledge exists at present for less than one-third of the land surface, that is, for less than 10 per cent of the earth's surface. Moreover, the older the rocks, the less accurate is our stratigraphic and structural knowledge. It is highly probable, therefore, that the actual number of orogenic epochs was many times greater than that recorded in the table, especially in the earlier periods.

The distribution in time of these epochs is of interest from the point of classification. Many lie at or near the end of traditional "periods," but by no means all. In the countries in which the periods were defined, no conspicuous crustal movements are recorded for the boundaries between Cambrian and Ordovician and the Pennsylvanian, Permian, and Triassic periods. For the latter, the absence of a decisive structural break is reflected in such stratigraphic terms as "Permo-Carboniferous" and "Permo-Triassic."

The lack of pronounced orogenic movements at the boundary of the Paleozoic and Mesozoic eras deserves attention. One wonders why in the discussion on the Mesozoic-Cenozoic boundary, so much was made of the idea that the "division between two of our biggest time units demands a decided break; it should involve strong diastrophism and extended erosion."[68]

In a number of cases, the pronounced faunal break occurred decidedly after the strong orogenic movements. This is true of the Triassic, Upper Cretaceous, Paleocene, Eocene, and the Oligocene[69] periods. Since practically all transcontinental correlation must be based on faunal characters, "an unconformity is not a practicable or suitable basis for a universal time-division"[70] anyway. This evident tendency of orogenic movements to refuse to fit in a simple way into our philosophical schemes should be a warning to us. Professor Victor Goldschmidt once said, with a sly smile, that with twenty years' experience he was not able to measure crystal faces at the goniometer

[68] F. Ward, "The Lance Problem in South Dakota," *Am. Jour. Sci.*, Vol. 7, 1924, p. 66.

[69] According to the definition here adopted.

[70] W. D. Matthew, "Fossil Vertebrates and the Cretaceous-Tertiary Problem," *Am. Jour. Sci.*, Vol. 2, 1921, p. 221.

with such accuracy that they would fall as neatly on their proper places in the gnomonic projection as many of his freshmen made them do when they used the goniometer and the gnomonic projection for the first time. It seems probable that the next generation will speak with the same generous smile of our efforts to make structural facts fit our ideas about stratigraphy.

For some orogenic movements there is clear evidence of two or more phases, following each other at short intervals in what may be considered as one orogenic epoch. These correspond apparently to the separate episodes of uplift which we recognized in the vertical rise of the central Andes and in the Sierra Nevada (pp. 394-401). It is almost certain that every one of the orogenic phases here listed would show such complexity if the structural record were adequate or had been studied in sufficient detail. Those who are quick to base stratigraphic correlation on structural relations should keep before them the possibilities of error inherent in this complexity.

So far, such distinct minor episodes of orogenic epochs have not been recognized in many regions. We have then no means to decide if they were contemporaneous in distant parts of the earth. Such behavior does not follow necessarily from the assumption that the epochs themselves were essentially synchronous. The process of deformation may well have begun at one point and spread gradually along certain mobile belts within the time interval of one epoch.

Bearing in mind the qualifications which arise from the uncritical state of our knowledge, we may now sum up the results of our analysis as follows:

Opinion 32. At least the more pronounced orogenic epochs produced deformation simultaneously in different parts of the world. Most if not all orogenic epochs consisted of smaller episodes. These may or may not have occurred contemporaneously in widely different regions.

The outcome of the preceding discussion is in harmony with the theoretical views developed in these pages. If orogenic deformation results from earth-wide crustal stresses, it is to be expected that the major effects are felt essentially "synchronously," that is, within an interval measured by hundreds of thousands of years (p. 401). The individual minor episodes, the sum of which constitutes the orogenic

epoch, need not coincide in different parts of even the same orogenic belt, though they may actually do so.

If, on the other hand, the process of orogenic folding resulted from the drift of floating continents, no synchronism of even the major deformations need exist. It is difficult to see why the different continents, so different in dimensions and in their positions on the surface of the rotating earth, should tear simultaneously from their moorings. In view of the conclusions reached at the end of the chapter on intrusions, however, we need not enter further into arguments along this line.

3. Beginning of Folding Versus Thickness of Sediments

When we consider the distribution of orogenic movements both in time and space, we are struck with the absence of any recognizable regularity. Strong deformation at one end of a series of welts, such as that of the Alps, left no recognizable record at the other end. Intense mountain making in one part of the earth's surface left others entirely unaffected. Earlier in this book we attributed this fitful behavior to the circumstance that only those parts of the crust suffered deformation which were weakest and by their topographic relation to all other parts most accessible to the action of crustal stresses.

In this discussion of the time relations of mobile belts we must note particularly that there is no relation between the thickness to which sediments accumulate and the time that elapses before the first orogenic movements set in.

In the Coast Ranges of California, folding occurred repeatedly during the Tertiary in basins in which only a few thousand feet of sediments had been laid down. Locally intense folding affected sediments which formed but a relatively thin veneer on an older basement of crystalline rocks.

In northern Alabama, on the other hand, the Appalachian geosyncline received something like 30,000 feet of sediments[71] from Cambrian to Pottsville time. Nearly one-third of this thickness was deposited during Cambrian time. Yet no pronounced orogenic movement seems to have affected this deep sedimentary trough until near the end of Paleozoic time.

[71] Ch. Butts, "Paleozoic Rocks," *Alabama Geol. Survey, Spec. Report 14*, "Geology of Alabama," 1926, p. 227.

Mansfield has recently published very careful measurements and estimates of the thicknesses of the formations he mapped in seven quadrangles located in the west-central portion of the Rocky Mountain region, in Idaho. Here approximately 45,000 feet of strata were laid down before an orogenic movement produced a strong deformation in this region. The sediments remained largely undeformed for the enormous interval from the Lower Cambrian to Upper Cretaceous time. Schuchert believes that "in the mid-length and width of the combined Cordilleran-Rocky Mountain geosynclines there was about 76,000 feet, or about 14 miles depth, of strata before the troughs evolved into synclinorial mountains."[72] Even if not all of this total thickness of sediments accumulated at any one point, it is large enough to prove Schuchert's generalization: "The amount of sediment in any of these troughs appears to have nothing to do with the time when they were folded into synclinoria. . . . Nor has the length of geologic time anything to do with the vanishing of the geosynclines." This conclusion may be formulated as follows:

Law 42. Neither a specific thickness of sediments nor any specific length of time are connected with the change from quiet geosynclinal sinking and sedimentation to folding under compressive stresses.

Since the publication of Reade's well known hypothesis,[73] the belief has been widespread that thermal expansion of the deeply depressed sediments of a geosyncline was responsible for at least an important part of their subsequent uplift and folding. The facts upon which this law is based show that such thermal expansion is at best negligible. The whole concept was based originally on erroneous ideas concerning the length of geologic time and the rate of sinking and sedimentation in geosynclines. Law 42, then, proves, at least as far as the thermodynamics of mobile belts are concerned, that they are not "Erdstreifen eigener Kraft."

Opinion 33. The cause for the change from geosynclinal sinking to mountain folding does not lie within the adjoining static columns of rock in mobile belts, but lies outside these belts in the dynamics of the whole crust.

[72] Ch. Schuchert, "Sites and Nature of the North American Geosynclines," *Bull. Geol. Soc. America*, Vol. 34, 1923, p. 208.

[73] M. Reade, *The Origin of Mountain Ranges*, London, 1886.

4. Decreasing Intensity of Crustal Deformation

Let us turn once more to Stille's table of orogenic epochs. As it is printed here, the few names at the bottom of the list do not give a fair picture of the duration of the Ordovician in comparison to the later formations, and the Cambrian is left out completely. Yet, Barrell estimated that the Cambrian and Ordovician combined amounted to 45 per cent of all Paleozoic time and nearly 30 per cent of all geologic time since the beginning of the Cambrian.[74]

Even if this estimate should prove too high, the fact remains that for this substantial part of post-Lipalian time orogenic movements seem to have been at a minimum. It seems as if an unusual period of rest had followed upon an unusual period of crustal unrest. In contrast to the beginning of post-Lipalian time, the last stages seem to have witnessed an unusual crowding of orogenic movements. It was pointed out above, that much of this seeming disproportion is merely the result of our relative ignorance concerning the earlier part of the record. Yet it is difficult to overcome the impression that there actually has been a certain amount of acceleration of orogenic movements towards the present. So long as our knowledge remains as incomplete as it is at present, we have no means of obtaining certainty on the question.

But whether there has been an increase in the number of recognizable orogenic movements or not, we can say with confidence that there has been a decided change in the visible results of these movements. This is expressed in the following law.

Law 43. Since Archeozoic time, the number and width of geosynclinal belts has grown consistently smaller.

In their broader aspect, the facts expressed in this law are generally recognized. So far as the writer knows, the Archeozoic rocks were strongly deformed everywhere on the face of the earth before the Proterozoic era began. The Proterozoic rocks, while not intensely affected everywhere, were deformed over a much larger part of the earth's surface than the Paleozoic. And finally, compared with the Paleozoic folding, that of Mesozoic and Cenozoic time appears much dwindled.[75] This has long been recognized. Suess put it into these

[74] J. Barrell, "Rhythms and the Measurements of Geologic Time," *Bull. Geol. Soc. America*, Vol. 28, 1917, pp. 884-5.

[75] See, for instance, the shaded areas in Fig. 23.

words: "The folding force was once active over the whole globe, but is restricted at present to particular regions."[76]

The best evidence of the diminution in the course of geologic time of the areas occupied by the orogenic belts is the progressive decrease in the width of the zones of crystalline schists and gneisses produced in successive eras. Since metamorphism increases with depth, comparisons of different orogenic belts must be made with regard to a definite level of reference. As such sea level alone is available. After all except the last great epochs of mountain making, erosion reduced the orogenic belts to such low relief that later epeirogenic movements carried the waters of the sea across the beveled structures. The ratio of newly formed crystalline schists to relatively unaltered sediments as seen on a tangential section across the orogenic belts taken near sea level, may then be taken as a rough measure of the amount of metamorphism produced by folding in the different eras.

For Archeozoic time, crystalline schists and gneisses occupy apparently 100 per cent of the folded belts so far as they are accessible to view today. For the Proterozoic, the percentage is still large, but much less than 100 per cent. The contrast between the Proterozoic and the Paleozoic is still greater. It is strikingly shown in the Appalachians. Similarly, in Europe, in the wide Paleozoic belts of intense orogenic deformation, crystalline schists and gneisses derived from Paleozoic rocks occupy only a small fraction of the surface over which the Mesozoic and later sediments transgressed eventually.[77]

Many of the post-Paleozoic belts of folding still stand more or less high above sea level. Yet erosion has gone deep enough to show that in the relatively short distance down to sea level no great increase in the distribution of highly metamorphosed rocks is to be expected. On the present surface, zones in which Mesozoic or even younger sediments have been metamorphosed into crystalline schists are rare, such as the Liassic Belemnite-bearing zoisite-garnet-staurolite schists of the Gotthard region in the Alps or the crystalline schists of Cretaceous age in Attica.

This comparison was made for each era for a plane lying near sea level. The writer knows of no observations that would justify

[76] E. Suess, *The Face of the Earth* (trans. by Sollas and Sollas), Vol. III, p. 4.

[77] See, e.g., the general discussion in S. von Bubnoff, *Geologie von Europa*, 2 Band, 1 Teil, Berlin 1920, pp. 644-67, esp. Fig. 200, p. 665.

the assumption that before the beginning of Proterozoic time erosion removed a vastly greater amount of rock in the interval between two orogenic phases than was removed between orogenic phases in the later eras. If, then, much larger areas of crystalline rock were exposed by erosion in earlier geologic times, we must conclude that metamorphic rocks were formed in greater quantities near the surface. This can only mean that the conditions favorable to regional metamorphism through orogenic deformation prevailed much nearer the surface during the Archeozoic than later. Since Archeozoic time there must have been a progressive change toward the present situation. What was the nature of this change?

The materials of the crust have remained the same. It must be the physical condition of the crust that has changed, either in structure, or thickness, or temperature, or two of these or all three combined. Since all later folding deformed a substructure which had already suffered a maximum of folding, metamorphism, and intrusion in Archeozoic time, it seems impossible that the structure could have changed materially during the later eras. This limits the change to the thickness and temperature of the crust.

In the chapter on intrusives, we recognized a similar change from Archeozoic to present time. There we arrived at a similar conclusion, starting from entirely different observations, namely, that the crust was thinner in Archeozoic time, with higher temperatures prevailing nearer the surface (p. 296).

In the earlier chapters we arrived at the conclusion that the structural history of the crust can be understood only as the result of alternating expansions and contractions of the crust. Here we add the idea that the algebraic sum of these opposite movements has not been zero, but has been negative, that is, has led to a thicker and less mobile crust. This means that there has been a significant loss of heat within the span of the geological record.

Opinion 34. The progressive reduction in the width of orogenic zones from Archeozoic time to the present is due to an increase in the thickness of the crust which has resulted from loss of heat from the outermost parts of the earth.

This leads directly to another idea which follows almost as a corollary:

Opinion 35. The alternating contraction and expansion of subcrustal matter is connected in some way and possibly controlled, at least in part, by fluctuations in the heat content of the subcrustal body of the earth.

We shall see in the last two chapters how well this conclusion fits into the hypothetical picture of diastrophism here developed.

5. Thermal History and Age of the Earth

In geologic circles, the idea is widespread that the length of geologic time revealed by the lead-uranium ratio in radioactive minerals is of an order of magnitude incompatible with physical computations concerning the age of the earth based on the mathematical theory of heat conduction. This misconception is based on a lack of appreciation of the simplified assumptions on which Lord Kelvin[78] based the computations which led him to grossly underestimate the age of the earth. He postulated the following conditions:[79]

1. The cooling body extends to infinity in all directions.
2. Its thermal conductivity is constant throughout.
3. At an initial epoch the temperature has had two different constant values on the two sides of a certain infinite plane.
4. The body is homogeneous.
5. It is isothermal.
6. There exists no source of heat within the solid.

Heaviside[80] has shown that by changing the first two assumptions so as to get nearer the actual condition of the earth, a value for the age of the earth may be obtained which is quite consistent with that obtained from radioactive minerals. His assumptions are:

1. The body is a finite sphere.
2. (a) The sphere is covered by a skin of a thermal conductivity different from that of the sphere (but so thin proportionately that its heat capacity may be ignored).
   (b) The thermal conductivity of the sphere is constant.

[78] Lord Kelvin, *Mathematical and Physical Papers,* Vol. III.

[79] The writer is deeply indebted to Professor H. C. Miller, of the University of Cincinnati, who prepared these concise statements of basic assumptions made by Lord Kelvin and by Heaviside.

[80] O. Heaviside, *Electromagnetic Theory,* Vol. II.

3. At an initial epoch the sphere had a constant temperature of zero throughout and was suddenly exposed to some superficial action which forever after kept the outer surface of the skin at a constant temperature *Vo*. (By considering *Vo* negative and by shifting the temperature scale, the solution of the problem is applied to a sphere initially above zero but whose surface is kept at zero temperature.)
4. The sphere is homogeneous.
5. It is isothermal.
6. There exists no source of heat within the sphere.

Conditions 4 to 6 are identical with the corresponding conditions used by Lord Kelvin. Introducing reasonable values for the constants used in his equation, Heaviside found a value of 9.55×10^9 years for the time required for the earth to cool to its present surface gradient. In this solution the presence of a source of heat in the outer skin is neglected (condition 6) but it would seem that the error thus introduced is of the order of magnitude of others arising from the choice of constants.

Inverting the process of reasoning, Holmes has shown that "from the age of the earth as fixed by the lead-uranium ratio in the oldest known rocks, from the present thermal gradient at the surface, and from the known amount of radioactive elements in superficial rocks the temperatures within the earth can be calculated" on the basis of the mathematical theory of heat conduction. Adams has shown that this computation leads to entirely reasonable results.[81]

This would not be the place to enter into a discussion of the mathematical-physical aspects of the question, even if the writer were competent to do so. The preceding remarks were inserted here merely to guard against a prejudice which he knows exists. It is fair to say that the assumption of a considerable loss of heat for the outermost layers of the earth is entirely consistent with the mathematical theory of heat conduction and the physical knowledge concerning the thermal condition of the earth.

But this loss of heat, if it really occurred, was shared by all parts of the crust, not merely by the mobile zones to which our attention

[81] L. H. Adams, "Temperatures at Moderate Depths Within the Earth," *Jour. Washington Acad. Sci.*, Vol. 14, 1924, pp. 459-72 (quotation on p. 472).

has been limited so far. Before we can feel confident that the hypothetical picture we have developed is adequate, we must extend our study to all of diastrophism. We must study epeirogenesis as the complementary phase to orogenesis in the complex process of crustal deformation. This we shall do in the following chapter.

CHAPTER XIII

EPEIROGENESIS

"I think it better to doubt until you know. Too many people assert and then let others doubt."
J. D. Dana, lecture epigram, quoted by G. P. Merrill.

1. Epeirogenic and Eustatic Movements of the Strand Line

The Problem. The twelve preceding chapters were devoted to the structure and the relationships in space and time of the orogenic belts of the earth. Like poorly healed scars the orogenic belts of our day cross the faces of the continents. Between them and outside of them lie the great flat expanses of plateaus and plains. If we could view the bottoms of the seas, the same contrast would stand out even bolder there. A discussion of crustal deformation must take into consideration also the deformation of the large areas outside the orogenic belts.

In contrast with the "mobile" belts, the flat continental surfaces are less mobile, but they are by no means rigid. Their deformation takes the form of swells and basins in contrast to the "welts" and "furrows" of the mobile belts. This qualitative difference is coupled with a quantitative one: The amplitude of deformation is small in "swells" and "basins" compared with that prevailing in "welts" and "furrows" (see p. 5).

The "broader displacements causing continents and plateaus, ocean beds and continental basins" Gilbert called "epeirogenic."[1] Downward movements of the past were recorded by sedimentation. Where the sea found access, they led to marine transgressions, with each successive stratigraphic unit extending beyond the preceding one in the direction of the submerging land. The chief record of upward movements of the past is found in surfaces of erosion. Unfortunately, the processes of erosion and sedimentation that record epeirogenic movements, are controlled by the level of the sea which is subject to independent movements. The record we observe is merely that of a

[1] G. K. Gilbert, "Lake Bonneville," *U.S. Geol. Survey, Mon. I*, 1890, p. 340.

shifting strand line. Let us examine the nature of this record more closely in an effort to separate the up and down movements of the land from the rise and fall of sea level.

The stratigraphic record. The story of the successive transgressions and regressions of the seas on the North American continent is told graphically by the series of stratigraphically detailed paleogeographical maps published by Schuchert in 1910 and the later maps contained in the two editions of his text-book.[2] These maps are, of course, only first approximations. But they give a vivid picture of the coming and going of epeiric seas, following shifting sea ways which are obviously the expression of broad down and up warpings of the continental surface. The picture is not that of an immobile land surface flooded and bared again and again by a rising and falling sea level. It is rather that of a passive, stationary sea level following the sinking and rising of parts of the continental surface under the action of deforming stresses. At any rate, the shifting of the sea ways from one period to another reflects differential movements of the land surface which are true epeirogenic movements.

But the epeirogenic movements are only a part of the diastrophic story as becomes evident when we enlarge our field of vision. For Europe the most detailed set of paleogeographic maps was drawn by De Lapparent.[3] Another interesting, though less detailed, set of maps is contained in Haug's large work.[4]

All paleogeographical maps, at least so far as they cover larger areas, will always be compound maps which show the maximum surface covered by the shifting waters of epeiric seas. Even such a generalized picture of the movements of these seas can be gained only from maps which cover relatively short time intervals. Looking over the European paleogeographical maps in the two works quoted above, we find that for a reasonably accurate comparison of the movements of epeiric seas in North America and Europe we have a sufficient number of maps only for the Devonian, and the Mesozoic, and Cenozoic periods.

[2] Ch. Schuchert, "Paleogeography of North America," *Bull. Geol. Soc. America*, Vol. 20, 1910, pp. 427-606, Pls. XLVI-CI, *idem*, *Historical Geology*, New York, 1st ed., 1915; 2nd ed., 1924; *Outlines of Historical Geology*, 2nd ed., New York, 1931.

[3] A. De Lapparent, *Traité de Géologie*, Vols. II and III, Paris, 1906.

[4] E. Haug, *Traité de Géologie*, Vols. II and III, Paris, 1908-1911.

For the Devonian, Schuchert's maps show an increasing flooding of the continent which reached its greatest extent in late Hamilton (1910, Pl. LXXVI) and Genessee-Portage time (1924, p. 313), followed by only a relatively slight decrease in Ithaca-Chemung time. De Lapparent's maps of Europe, covering larger time intervals, show a great increase for the Middle Devonian over the early Devonian, and only a relatively small regression in the late Devonian. There is obviously a parallelism of events in the two continents for this period. For the later Paleozoic, the number of maps is inadequate. But the significant prevalence of terrestrial deposits with gypsum and salt is evident in both continents during the Permian.

The North American maps for the Jurassic show well the pronounced transgression in the "Early Upper Jurassic" (Schuchert 1924, p. 505). The seven maps in De Lapparent's book give a fair picture of the great flooding of Europe in Jurassic time, which culminates in the earlier half of the Upper Jurassic (pp. 1211, 1225, 1239). Similarly, the greatest transgression of Upper Cretaceous time is shown in Europe for Turonian time, that is, the earlier part of Upper Cretaceous (p. 1420) and in North America, for Benton time (1924, p. 557), which is roughly contemporary. In the case of the Triassic and Lower Cretaceous periods, there is less obvious parallelism.

The writer has purposely given space to this comparison of paleogeographic maps, although he is well aware of their insufficiency. Those who speak disparagingly of these graphic records should remember that such maps are no more inaccurate than knowledge was at the time they were drawn. They would be far more valuable if they existed for shorter intervals and, above all, if they were available not only for times of great transgressions but also for times of great regressions. Schuchert's maps for the earlier Paleozoic (1910) are especially useful in this respect.

The chief value of such a comparative study of sufficiently detailed, modern paleogeographic maps lies in the vivid impression it gives of the peculiar combination of highly variable local movements with a broader rhythm which is common to the continents. In 1888 appeared the second volume of Suess' *The Face of the Earth* in which, for the first time, the stratigraphic experience in all continents was focused in an encyclopedic fashion on the larger problems of oceanic transgressions and regressions. Every student of these problems must

go back to this classic treatment. In the last summary chapter Suess expresses the opinion that a cause quite different from diastrophic movements in the common sense of the word must underlie the rhythm of world-wide changes which dominates the transgressions and regressions of the seas. Referring to the most striking illustration he says:

"The middle Cretaceous transgression presents itself on the Amazon, the Athabasca, the Elbe, the Nile, the Tarym, and the Narbada, in Borneo and Saghalien, and on the Sacramento; it marks a general physical change which affected the whole surface of the planet. In this lies the explanation of the remarkable fact that it has been found possible to employ the same terminology to distinguish the sedimentary formations in all parts of the world. This would have been impossible if the limits of the formations had not been drawn by natural processes simultaneously in operation over the widest areas.

"It has been fortunate for stratigraphical geology that its earliest development took place in England, a region where the frequency of gaps in the stratified series neither rises above nor falls below the mean, a region which has at times been submerged beneath the sea, at others covered by freshwater lakes or left exposed as dry land. . . . The limits of the formations established by William Smith and his successors correspond for the most part with negative phases. Where they have been most precisely studied, as in the case of the limit between the Jurassic and Cretaceous, our knowledge has been extended into details, and we now perceive that by a movement in the negative direction arms of the sea become isolated and the fauna impoverished, although its final extinction may be delayed till the negative movement has passed its maximum.

"In this also we find an explanation of the difficulties which were encountered in correlating the stratified series where it attains its complete marine development, as in the Eastern Alps, with the succession established in England. In this again we recognize the source of the opinion expressed by many eminent investigators to the effect that this succession stands in relation to certain cycles, i.e., a perpetually recurring alternation produces a periodic return of similar conditions."[5]

[5] E. Suess, *The Face of the Earth* (trans. by Sollas and Sollas), Vol. II, 1888 (date of original edition; translation issued in 1906), pp. 540-1.

Over four decades have elapsed since Suess drew this picture of the major transgressions and regressions of the sea and their influence on marine faunas. Stratigraphic knowledge has increased in geometric progression in all parts of the world and everywhere the essential correctness of Suess' generalization has been borne out. It is here restated in the form of a law.

Law 44. In a large way, the major movements of the strand line, positive and negative, have affected all continents in the same sense at the same time.

Coastal terraces. This law applies strikingly to the present day. All continents stand relatively high with reference to sea level. Nowhere is there an area of continental dimensions that is largely submerged beneath epeiric seas. The record of the last upward movements is found strikingly preserved in the coastal terraces which surround the present-day continents. There are abundant evidences of oscillatory movements but generally with the negative displacement of the strand line prevailing. Ten years ago Depéret emphasized that coastal terraces may be traced consistently from the shores of the Mediterranean to those of France and Great Britain.[6] The interval between successive terraces tends to be remarkably constant.[7]

Recently Dubois,[8] Antevs,[9] and Cooke,[10] the last-named most categorically, have expressed the opinion that the terraces of our own

[6] Ch. Depéret, "Essai de coordination chronologique générale des temps quaternaires," *Acad. Sci., Compt. Rend.*, Paris, Vols. 166 and 167, 1918; 168, 1919; Vols. 170 and 171, 1920. Summarized in: "La classification du Quaternaire et sa corrélation avec les niveaux préhistoriques," *Soc. Géol. France, Compt. Rend.*, 1921, pp. 125-7. English abstract in H. F. Osborn and Ch. A. Reeds, "Old and New Standards of Pleistocene Division in Relation to the Prehistory of Man in Europe," *Bull. Geol. Soc. America*, Vol. 33, 1922, p. 422-39.

[7] See, for instance, Général de Lamothe, "Les anciennes lignes de rivage du Sahal d'Alger," *Mém. Soc. Géol. France*, 4e sér., I. Mem. No. 6, 1911; *idem*, "Aux sujects du déplacement de la ligne de rivage le long des côtes Algériennes pendant le Post-Pliocène," *Bull. Soc. Géogr. France*, Vol. 12, 1912; Gignoux, "Résultats généraux d'une étude des anciens rivages dans la Mediterranée occidentale"; *Ann. Univ. Grenoble*, Vol. 23, 1911.

[8] Georges Dubois, "Sur la nature des oscillations de type atlantique des lignes de rivages quaternaires," *Bull. Soc. Géol. France*, Vol. 25, 1925 (publ. 1926), pp. 857-78.

[9] Ernst Antevs, "Quaternary Marine Terraces in Non-Glaciated Regions and Changes of Level of Sea and Land," *Am. Jour. Sci.*, 5th ser., Vol. 17, 1929, pp. 35-49.

[10] C. Wythe Cooke, "Correlation of Coastal Terraces," *Jour. Geol.*, Vol. 38, 1930, pp. 577-89. ". . . The conclusions reached . . . , if valid, apply not only to the broad plains along the southeastern Atlantic seaboard of the United States, with which the paper deals specifically, but to the entire world" (p. 577).

Atlantic coast represent similarly continuous systems. Much more detailed work will be needed to convince us that coastal terraces along many thousands of miles of shore can be traced continuously in spite of local deformations. While it seems probable that the system will not show the impressive simplicity of Depéret's and Cooke's concepts, the terraces that have long been known are continuous over such distances that they cannot be ascribed to the type of crustal movement normally referred to as "diastrophic." Suess thought that "even as the transgressions of the ancient periods are much too extensive and uniform to have been produced by movements of the lithosphere, so too are the displacements of the strand line in the immediate past. . . . Movements of the lithosphere do not explain why the stratified series presents the same lacunae in the United States and in central Russia, nor do they explain the formation of long horizontal strand lines in complete independence of the structure of the land."[11]

Suess designated those changes of the strand level "which take place at an approximately equal height, whether in a positive or negative direction, over the whole globe" as "eustatic movements."[12] For reasons to be given later, the writer considers it advisable not to stress the phrase "at an approximately equal height" and to add the expression "simultaneously." Eustatic movements, then, are such displacements of the strand line as affect all parts of the globe essentially simultaneously in the same sense.

The step-like rise of the terraces on our Atlantic and Pacific coasts as well as those of Europe and other continents must be the result of a series of intermittent rises or of oscillations in which the negative vertical displacements always exceeded the positive oscillation. It represents a downward movement of the sea level with reference to the continental level or a rise of the latter with reference to the former.

Topographic rejuvenation. Lately systematic physiographic studies in the lands east of the Mississippi River have led to the conclusion that a large part of the relief of the plateau lands is due to repeated

[11] E. Suess, *op. cit.*, pp. 550, 552.

[12] *op. cit.*, p. 538.

relatively recent uplift.[13] The diagram reproduced in Fig. 93[14] shows the nature of the evidence which is exhibited in convincing fashion in

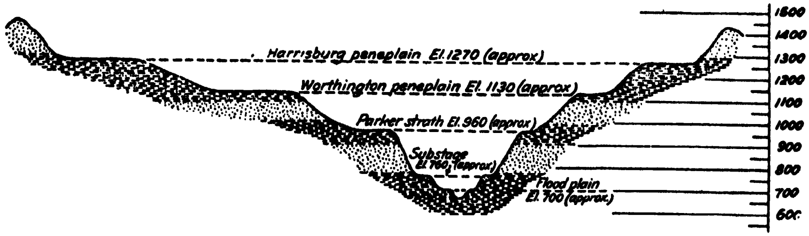


Fig. 93. Diagrammatic section showing the partial peneplains and narrower planation levels ("straths") in Columbiana County, eastern Ohio.
(Wilber Stout, 1924)

southern Ohio, and in the plateau regions of West Virginia and Pennsylvania. Here also much careful detailed work remains to be done before the history can be set forth with confidence. But there is little doubt that the relatively recent progressive rejuvenation is the counterpart inland to the coastal terraces and tells the same story. It is to be expected, by analogy, that similar rejuvenation characterizes large parts of the other continents.

It is, in fact, true that nowhere on the earth is there known to exist an example of a peneplain developed in the humid cycle and still lying near the base level of erosion. This fact was held up by Tarr as an argument against Davis' concept of the peneplain in its extreme form as early as 1898[15] in a paper that is still well worth reading. We are not concerned here with the question whether the actual end product of prolonged subaerial erosion is a "nearly featureless plain" (Davis) or "merely a greatly reduced but still markedly irregular surface" (Tarr). But we must be impressed by the uniformity with which re-

[13] Wilber Stout, "Geology of Muskingum County," *Ohio Geol. Survey, Bull. 21,* 1918, pp. 15-20; *idem,* "Geology of Columbiana County," *ibid., Bull. 28,* 1924, pp. 36-45; *idem,* "Geology of Vinton County," *Bull. 31,* 1927, pp. 34-42; Frank Leverett, "Studies of Pleistocene Phenomena of Ohio River Basin," Abstract in *Science,* Vol. 63, 1926, pp. 484-5; *idem,* "The Pleistocene of Northern Kentucky," *Kentucky Geol. Survey,* Series VI, Vol. 31, 1929, pp. 18-28. Also as yet unpublished studies by L. S. Brand on pre-Illinoian topography of the Cincinnati region, extended into Kentucky by L. Desjardins.

[14] Reproduced from Wilber Stout, *Ohio Geol. Survey, Bull. 28,* Fig. 2, p. 39.

[15] R. S. Tarr, "The Peneplain," *Am. Geologist,* Vol. 21, 1898, pp. 351-70. This objection has been voiced since, especially by European opponents to Davis' deductive concepts.

juvenated "peneplains" are reported from all parts of the world both from plateau lands and in mountains. Some very general if not universal process must have taken place in the immediate past which caused this rejuvenation.

With this broadened view of the latest crustal changes before us, we turn to the attempts that have been made to explain the phenomenon of eustatic movements of the strand line. Are they also due, in the last analysis, to crustal movements or do they arise independently?

2. Eustatic Movements Due to Glaciation and Deglaciation

Changes in water content of ocean basins. In a limited area the stair-like fringe of coastal terraces looks like the border of terraces which surrounds the Great Lakes, Lakes Bonneville and Lahontan, and their counterparts in other continents. Those lacustrine terraces came into existence solely through a shrinking of the water volume, without any changes in the form and depth of the basins. To account for the marine terraces in the same way would require proof that there has been, at least throughout most of Pleistocene time, a diminution of water in the ocean.

The quantity of oceanic water is, of course, by no means constant. Hydration of minerals, such as goes on all the time on a large scale in weathering, constantly removes water from circulation, while volcanic processes furnish juvenile water in quantities. Similarly climatic changes alter the proportion of water held in the ground to that kept in circulation. The algebraic sum of these two processes, working in opposite directions, varies incessantly but slowly and through long intervals.

The only process that results in changes of sufficient magnitude at a sufficiently fast rate to enter into the problem of marine coastal terraces is the glaciation and deglaciation of the high latitudes and altitudes. Two movements of the strand line were clearly caused by the last deglaciation: the rapid negative movement along the shores surrounding the Baltic and Canadian shields indicated by the highly elevated terraces, and the rapid positive movement shown by the recent great development of corals on deeply submerged erosion platforms.

Elastic recovery after deglaciation. An unusual amount of detailed field work has made it possible to draw contours ("isobases" or, better, "isanabases") which depict the total risé of land since the melting back of the last ice sheet. Fig. 94 shows this map in the form pub-

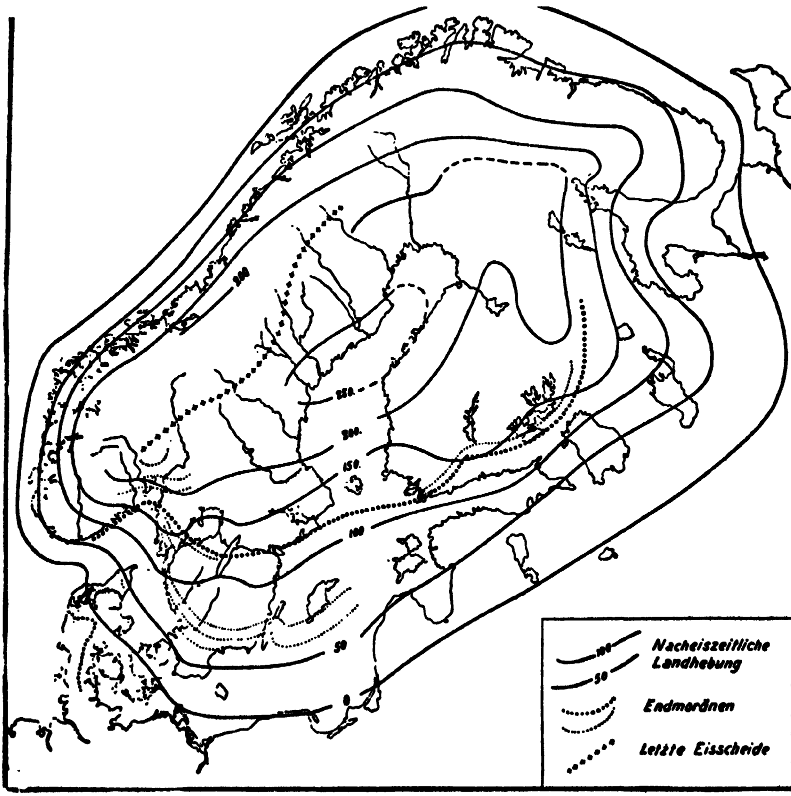


Fig. 94. Map of Fennoscandia showing the amount of post-glacial rise by means of contours (isobases).

(A. G. Högbom, 1913; reproduced from *Handbuch der regionalen Geologie*, by permission of Carl Winters Universitätsbuchhandlung)

lished by Högbom.[16] The highest point of the post-glacial strand line lies 284 meters (931.7 feet) above the present sea level. In a recent concise summary of knowledge concerning this post-glacial rise,

[16] Reproduced from A. G. Högbom, "Fennoscandia," *Handbuch d. regionalen Geologie*, 13. Heft, Heidelberg, 1913, p. 131, Fig. 32.

Högbom points out several sources of error all of which make this rise appear too small. The chief of these is the fact that the highest strand line could only form after practically all ice had disappeared. Since there is good reason for believing that the upward movement was in progress while the ice melted away, a substantial part of the upward movement remained unrecorded. He estimates that the actual maximum uplift of the ice divide in the center of Scandinavia amounted to[17] 300 or 400 meters.

Owing to the celebrated researches of DeGeer and his students on varved clays,[18] it has been possible to date the rate at which the strand line receded from different parts of Scandinavia through the last ten thousand years. Fig. 95 shows Högbom's time-curve[19] of this recession of the strand line. On the abscissa are marked seven millenniums before Christ ($\pm$ 0) and two after Christ. The ordinate marks elevations above sea level measured in meters. Thus the highest point shows that some 6,700 years before Christ the strand line stood in Angermanland at a point which now lies about 270 meters (886 feet) above sea level. Five thousand years later it had dropped in this region to a point now about 60 meters (197 feet) above sea level. The lower right hand corner marks the present sea level.

This curve shows not only a remarkably rapid decrease in the rate of the strand movement, but a most significant difference in the behavior of the marginal and more central regions. The former are represented in the diagram by the two lower curves, one for Kalmar on the east coast of southern Sweden, the other for the Great Belt, the largest of the arms that connect the Baltic with the North Sea. The line from *C* to *D* marks a rise of sea level, that is, a submergence; that from *D* to *E* an emergence, and from *E* to *F* another submergence followed by the slow emergence that led to the present level.

Similar minor down and up oscillations of sea level since the recession of the continental ice have occurred in North America. They,

[17] A. G. Högbom, "Epeirogenetische Bewegungen" in Wilhelm Salomon, *Grundzüge der Geologie,* Teil I, 1922, pp. 175-203.

[18] For a first introduction to this method, DeGeer's early account still is unsurpassed: G. De Geer, "A Geochronology of the Last 12,000 Years," *Cong. géol. intern., XI, 1910, Compt. Rend.,* 1912, pp. 241-53. Much of the later literature is quoted in E. Antevs, "Retreat of the Last Ice-Sheet in Eastern Canada," *Canada Geol. Survey, Memoir 146,* 1925.

[19] Reproduced from A. G. Högbom, *Bull. Geol. Inst. Upsala,* Vol. 16, 1919. (Here taken from *op. cit.,* 1922, p. 188, Fig. 7.)

like the rapid post-glacial rise of the centers of glaciation, must be directly connected with the removal of the ice load. Both elastic and

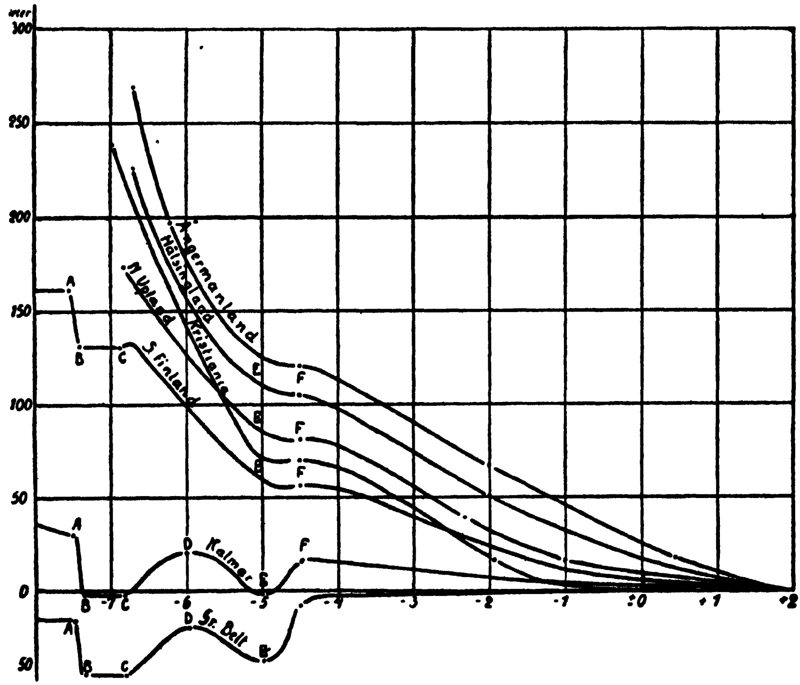


Fig. 95. Graph showing the position of the shore line in different parts of Fennoscandia in the interval from 8000 B.C. to the present.

The elevation above sea level is given by the ordinates. The abscissae begin with —8 = 8,000 years B.C. +2 = the present.

(A. G. Högbom, 1913; reproduced from *Grundzüge der Geologie*, by permission of E. Schweizerbart'sche Verlagsbuchhandlung [Erwin Nägele])

non-elastic deformations of the crust must have been involved in this reaction of the crust.[20] In what proportion these two factors entered can hardly be determined at present. Daly has recently given a discussion, based largely on mathematical developments by Rudzki, which brings out emphatically what complicated effects may be expected from purely elastic deformation.[21]

[20] J. Barrell, "Factors in Movements of the Strand Line and Their Results in the Pleistocene and Post-Pleistocene," *Am. Jour. Sci.*, 4th ser., Vol. 40, 1915, pp. 13-21.

[21] R. A. Daly, "Pleistocene Changes of Level," *Am. Jour. Sci.*, 5th ser., Vol. 10, 1925, pp. 281-313.

Submergence of erosion platforms through deglaciation. Outside the immediate vicinity of the glaciated regions, the possible elastic effects due to the removal of the Pleistocene ice caps must have been overshadowed by the simple eustatic rise of sea level due to the melting of the ice. In the paper quoted above, Daly has listed the estimates of the rise of sea level due to the addition of water of deglaciation made by numerous writers since 1842, and discusses the large sources of error. He concludes that a shift of the strand line of fifty to sixty meters represents the right order of magnitude.[22] This agrees well with the average depth below sea level of the platforms which surround most islands bearing coral reefs. This coincidence is the basis of the glacial-control theory of coral reefs of which Daly has become the chief exponent.[23] It assumes that the great development of coral reefs in latest geologic time is due largely to the gradual rise of sea level above its low position during maximum glaciation which was low enough at least to keep the platforms scoured clean and to prevent coral growth. It is quite possible that during maximum glaciation in each glacial epoch the sea actually dropped to near its former low level and enlarged the wave-cut platforms by further cliff cutting.

Since the times of maximum glaciation were only a small fraction of the Pleistocene, it is generally thought that they were too short to produce the relatively wide submerged platforms. R. T. Chamberlin secured the opinions of ten American glacial geologists concerning the relative lengths of glacial and interglacial epochs. Averaging their answers, he arrived at the following figures:[24]

Combined stages of maximum glaciation	4 per cent
Combined stages of advancing and retreating ice-sheets	16 per cent
Total of interglacial epochs	80 per cent
Total Pleistocene time	100 per cent

He concludes, "The brief duration of the low-level glacial-control

[22] R. A. Daly, *op. cit.*, pp. 284-9.

[23] *idem*, "Pleistocene Glaciation and the Coral Reef Problem," *Am. Jour. Sci.*, Vol. 30, 1910, pp. 297-308; *idem*, "The Glacial-Control Theory of Coral Reefs," *Proc. Am. Acad. Arts and Sci.*, Vol. 51, 1915, pp. 158-251; *idem*, "The Coral-Reef Zone during and after the Glacial Period," *Am. Jour. Sci.*, Vol. 48, 1919, pp. 136-59.

[24] R. T. Chamberlin, "The Geological Interpretation of the Coral Reefs of Tutuila, American Samoa," *Carnegie Inst. Washington, Pub. 340,* 1924, p. 172.

wave-attack must greatly lessen its importance as a factor in the erosion of oceanic shores."

One might argue that the times of maximum glaciation may also have been times of greatest storm activity. The storms may have been twice or three times as frequent as they were in interglacial times and their average intensity may have been twice or three times as great. Since the kinetic energy of moving particles grows as the square of their velocity, and since practically all wave-cutting is accomplished in consequence of storms, it remains possible that relatively great erosional work may have been accomplished in low latitudes during the small fraction of Pleistocene time when continental glaciation was at its maximum. The writer believes it to be more probable, however, that the terraces on which the coral reefs of the Pacific Ocean grew, came into existence before Pleistocene time, when the islands stood relatively higher, and that they were merely swept clean during the times of greatest glaciation. If this is true, Darwin's original idea, that the floor of the Pacific has been lowered with reference to the level of the continents, remains valid.

We arrive at the conclusion, then, that the two topographic features which were brought about by deglaciation—the greatly elevated terraces of northern shores and the coral reefs of equatorial waters—in the last analysis both owe their existence to crustal deformation: one to rebound of the crust upon removal of the ice load, the other to subsidence of the ocean floor in pre-glacial or glacial times.

3. Eustatic Movements Due to Changes in Crustal Relief

Greatest possible rise of sea level due to deglaciation. If the deeply submerged platforms of the coral islands and less obvious corresponding features of our coast mark the low stand of sea level during epochs of glaciation, there must exist a corresponding wave-cut platform which was cut and enlarged in the successive long interglacial epochs. We might even look for a whole series of such terraces. We must now face the question whether the great systems of coastal terraces of North America, Europe, and the other continents owe their existence to just this process.

Let us approach the question by asking how high the level of the sea would rise if there were no change in the crustal relief and if all water now stored in the polar ice caps were released.

Daly quotes the following estimates for the rise of sea level which would result from the melting of the existing polar ice caps:[25]

W. B. Wright	(1914)	40+ meters
R. A. Daly	(1915)	11–37 meters
W. J. Humphreys	(1915)	40 meters
Fr. Nansen	(1922)	15–25+ meters

Recently Antevs has computed a possible rise of sea level of from 40 to 60 meters (130 to 200 feet).[26]

Height and age of Atlantic coast terraces. Compare with these figures the typical elevations which Cooke gives for the terraces of our Atlantic shore south of New York:[27]

81 meters (265 feet)
65 meters (215 feet)
49 meters (160 feet)
29 meters (95 feet)
20 meters (65 feet)
8 meters (25 feet)

From these figures it is evident that at least the highest of the terraces cannot possibly have been formed without a permanent displacement of sea level with reference to the continents. The others all lie within possible reach of the oscillations due to changes in the dimensions of the polar ice caps.

The physical condition of the terraces proves, however, that their formation must have reached back through a time interval comparable to that of the whole Pleistocene. In the Susquehanna River Valley, Leverett[28] has traced an Illinoian valley train into the Wicomico formation, that is, into the 29 meter (95 feet) terrace. In Europe, more extended evidence points in a similar way to the ages of the terraces extending through the whole of Pleistocene time. This means that the stair-like sequence of these terraces could have come into existence without change in the relative position of the continents and the interglacial sea level only, if each successive interglacial period was colder, leaving more water locked up in polar ice caps than the preceding one.

[25] R. A. Daly, 1925, *op. cit.*, p. 285.

[26] E. Antevs, 1929, *op. cit.*, p. 43.

[27] C. Wythe Cooke, 1930, *op. cit.*, p. 588.

[28] Frank Leverett, "Results of Glacial Investigations in Pennsylvania and New Jersey in 1926 and 1927," *Bull. Geol. Soc. America*, Vol. 39, 1928, p. 151.

Cooke definitely states this as a possible explanation of the coastal terraces. Nothing, however, in the extent and character of the glacial and interglacial deposits bears out such a conclusion. On the contrary, the whole picture of Pleistocene glacial history is altogether incompatible with it.

Conclusion. It seems much more reasonable to assume that during interglacial times the world climate was not essentially different from that of the present, including the existence of polar ice caps comparable to those of today. This would mean that the present volume of oceanic water is essentially that which existed in interglacial times. Each interglacial period, then, would have found the former strand line actually lifted with reference to its original level, and our coast terraces would represent the record of a progressive displacement of the interglacial sea level with reference to the continents by differential vertical movements of the surface of the crust.

To the writer this seems the only acceptable interpretation of the stairway of coastal terraces. Their origin, in its major aspect, seems due to peculiar diastrophic movements. The horizontality of especially the younger terraces, remarkable for the insignificant amount of warping present, makes it seem impossible to look to upward deformation of the continents caused by horizontal compression as the chief cause of the negative strand displacement as Suess had seen clearly. "Downwarping or downfaulting of part of the sea bottom" is, therefore, generally held responsible for the change.

But "downwarping or downfaulting" of the sea bottom is too specific language for the purely hypothetical process to which we must appeal for the world-wide eustatic movements with which we are concerned here. The writer prefers to speak merely of an increase in the average crustal relief, that is, the difference between the average elevation of the continents and ocean bottoms, leaving the question undecided whether the sea bottom alone was responsible for the change or, if not, whether perhaps in some way the crust as a whole may have been involved. We are not even in a position to say whether the assumed deformation of the sea bottom should be thought of as of "orogenic" or of "epeirogenic" nature. All we can safely conclude is this:

Opinion 36. The major eustatic movements of the sea are the result of changes in the vertical distance between mean levels of ocean floors and continental surfaces.

The whole problem of the Pleistocene changes of sea level was introduced here in order to let it be seen in proper perspective. They represent only a detail of the greater phenomenon of eustatic changes of sea level. The geologic "tide" of the sea rises through ages to conquer the land, and then again sinks, causing the continents to emerge high above it. We cannot be content to assume purely accidental local downward displacements of the sea floor to account for the few little steps of the last emergence which are recorded in the terraces of modern coasts. We must regard those last diastrophic movements of the sea floor as part of a greater rhythm of crustal movements. In order to do so, we leave the Pleistocene terraces and return once more to the broader stratigraphic record of eustatic changes of sea level throughout historical geological time. We must ask ourselves the question, what relation the great eustatic movements of the sea bear to the episodes of orogenic deformation.

4. Time Relations of Epeirogenic and Orogenic Movements

Marine transgressions versus orogenic episodes. The preceding discussion led to the conclusion that the major eustatic movements of the sea are the result of changes in the vertical distance between ocean floors and continental surfaces. The rhythm of these major eustatic movements might be expected to bear any one of three possible relations to that of orogenic movements. (1) Major eustatic movements which result in great regressions of the sea might accompany times of major orogenic deformation. (2) The two might alternate, so that great transgressions of the sea would take place at times when orogenic deformation caused many geosynclinal belts to rise above sea level. (3) Finally, the two rhythms might be wholly independent of each other, their results now coinciding, now occurring at different times.

The first has long been recognized as corresponding most nearly to the actual events of the geological past. The most satisfactory evidence is obtained from a study of the incidence in time of those events which left a tangible record, the great marine transgressions and the great orogenic deformations. The records of marine regressions as

well as the records of periods of crustal rest are largely negative, and the results of minor events may be obscured by local conditions. Neither is apt to carry conviction.

For a record of the great marine transgressions of the North American continent, independent of theories concerning diastrophism, we turn once more to the latest edition of Schuchert's paleogeographic maps.[29] It is fortunate, for our purposes, that of all epochs within one geological period, the one which shows the greatest flooding of the continent is almost always sure to be represented by a map. On these maps we find maxima of transgression indicated corresponding to the following positions in the stratigraphic time-scale:

TABLE VII

Table Showing Stratigraphic Position of Major Marine Transgressions in North America

NORTH AMERICA	APPROX. EUROPEAN EQUIVALENTS
Early Upper Cretaceous (Benton)	Turonian
Early Upper Jurassic (Sundance)	Oxfordian
Late Upper Triassic (Upper Norian)	Upper Norian
Latest Pennsylvanian and Earliest Permian	Upper Stephanian and Lower Autunian
Late Lower Mississippian* (Burlington)	Tournaian
Early Upper Devonian (Genessee-Portage)	Frasnian
Late Middle Silurian (Upper Lockport)	Upper Wenlock
Late Upper Ordovician (Middle Richmond)	?
Early Middle Ordovician (Early Mohawkian)	Caradocian
Middle Upper Cambrian (Late Croixian)	Upper Cambrian

*Ch. Schuchert, *Historical Geology*, 1st ed., 1915, Pl. XIX, p. 733. No paleogeographical maps are given for the Mississippian in the second edition.

Turning next to Stille's table of orogenic epochs (Table VI, opp. p. 413), we proceed to compare these episodes of great flooding of the North American continent with those of mountain making. Again we base our confidence in such a comparison on the fact that we are concerned only with major movements. While it is, of course, true that Stille's table is far from being complete, it is probable that it records most of the major epochs of orogenic deformation.

[29] Ch. Schuchert, *Historical Geology*, New York, 1924.

A comparison of the two tables proves conclusively that the great marine transgressions of the North American continent did not coincide in any way with orogenic episodes.

Law 45. The great transgressions of the sea upon the continents occurred in the intervals between the larger orogenic episodes.

Since the publication of the second volume of Suess' *Das Anlitz der Erde*, much attention has been given in treatises on stratigraphic geology to the transgressions of the seas. So long as sufficient regional information is lacking to warrant the drawing of detailed paleogeographical maps for all the continents, it is quite impossible to formulate an adequate picture of the algebraic sum of all the local advances and recessions of the sea which resulted at all times from differential deformations of the surface.

The second half of Stille's great work, *Grundfragen der vergleichenden Tektonik*, contains a verbal summary of strand line movements since Cambrian time[80] compiled for just this analysis with which we are here concerned. His data bear out the writer's conviction that we are justified in extending to the whole earth the scope of law 45 which was derived primarily from a consideration of North American stratigraphy.

Stille emphasizes especially the negative movements of the strand line in times of strong orogenic deformation. Thus, for instance, one of the greatest marine regressions in North America is that which occurred at the end of the Mississippian.[81] Negative movement of the strand line was similarly important in Europe. Stille calls it "ganz ausserordentlich."[82] It coincides with the great "Sudetic" epoch of folding which affected the inner zone of the Variscan Mountain belt of Europe, the Wichita and Ouachita Mountain belts of North America, and other parts of the world.

Stille arrives at the conclusion that an upward movement of the continents with reference to the level of the sea and a corresponding recession of the waters of the sea coincide in time with the effects of horizontal compression. From this he concludes that the two effects

[80] Hans Stille, *Grundfragen der vergleichenden Tektonik*, Berlin, 1924, pp. 281-369.

[81] An excellent study of this great stratigraphic break has just been published by A. I. Levorsen: "Pennsylvanian Overlap in United States," *Bull. Am. Assoc. Petrol. Geol.*, Vol. 15, 1931, pp. 113-48.

[82] Hans Stille, *op. cit.*, p. 306.

stand in a causal relation to each other.[33] The writer accepts this conclusion as valid without going into further details of the evidence much of which may be read in Stille's book.

Opinion 37. Times of crustal compression tend to be times of increased crustal relief outside of the mobile belts, that is, of greater elevation of the continental areas above the ocean floors.

Local versus world-wide epeirogenic deformation. This conclusion is in a large measure contrary to a relation which Haug thought to be sufficiently general to be called a law. Haug's view of the geosynclinal belts as continuous bands which divide the earth's surface into a number of intergeosynclinal segments is more rigid and literal than that of the present writer. To Haug all intergeosynclinal segments are potential continental areas, even where at present they coincide with oceanic abysses. Between these rigid segments and the geosynclinal belts there is an interplay such that at times the waters of the sea tend to be gathered into the geosynclines leaving the continental areas high and dry, more or less, while at others the geosynclinal areas rise above sea level causing the ocean waters to spread over the continents in great transgressions. In this extreme form Haug's view is the exact opposite of that of Stille and of the present writer.

The writer does not propose to go into a discussion of the evidence against this "law," since Stille has done so in considerable detail. The reader is referred to his book.[34]

There are, however, many cases in which, in limited areas at least, reciprocal movements took place between geosynclinal furrows and adjoining continental areas. Haug's view arose from an exaggerated estimate of such occurrences. The more detailed our knowledge grows concerning paleogeographic changes, the more we recognize that no simple relation exists between the deformations of any relatively small portion of a geosynclinal belt and the transgressions and regressions of the sea over adjoining continental areas. For any limited area, the actual movements of sea level with reference to the land surface are the result of at least three major factors:

(a) Differential deformation of small amplitude involving the whole local land surface (local epeirogenic movements).

[33] Hans Stille, *Grundfragen der vergleichenden Tektonik*, Berlin, 1924, p. 364.
[34] *ibid.*, pp. 322-47.

(b) Differential deformation of larger amplitude in local mobile areas (local orogenic movements).

(c) Movements of sea level registering the algebraic sum of all crustal movements over the whole earth's surface (eustatic movements of sea level).

For any limited region within a limited interval of time the superposition of the effects of these three factors should be as complicated as we find it to be. But if we could survey the movements of all land and water over a number of periods, we would find a relatively simple rhythm clearly expressed during times of major orogenic activity and during major "anorogenic" times, as Stille calls them. In the earlier stages of orogenic epochs, much folding takes place in which the horizontal component of movement greatly exceeds the vertical uplift. In the later stages, vertical movement predominates in the orogenic belts. At the same time, an upward movement affects more or less all the continents, that is, the times of major crustal compression are also the times of a general elevation of the continental areas. The resulting great regressions produce the major divisions of our stratigraphic time-scale.

Between major orogenic epochs, the seas tend to invade old and new geosynclinal waterways and eventually spread far and wide over the continental areas. These are thought to be the times of major crustal tension.

Eustatic effects of changes in surface area of earth. This picture seems to fit the stratigraphic record. But it involves two difficulties. One is a problem of space relations. According to the view adopted in these pages, the periods of crustal tension result from subcrustal expansion. While they last, the earth's surface is supposed to grow materially larger, by the addition perhaps of hundreds of thousands and even millions of square miles.

Much of this expansion must generally be distributed over the oceanic areas. This increase in the size of the ocean basins should cause a fall of sea level and world-wide regressions, the exact opposite of what we assume to be true.

Conversely, crustal compression should cause a corresponding diminution of the oceanic areas which should raise the level of the sea and send it transgressing across the continents in spite of their increased elevation.

The question is: How large is this contrary effect of changes in the dimensions of the earth?

Kossinna gives the following figures for the dimensions with which we are here concerned:

volume of ocean:	1370×10^6 km.^{3}
mean depth of ocean:	3.8 km.
area of ocean:	360.5×10^6 km.^{2}

Let us assume that in the course of a major orogenic epoch folding and thrusting take place along two mobile belts, both lying entirely within oceanic areas. Assume further that each has the length of a great circle and that over the whole length of each of these circles the shortening of distances measured across each belt amounted to 100 kilometers. The total loss of surface would then be

$$2 \times 40.000 \text{ km.} \times 100 \text{ km. } \textit{or}$$
$$8 \times 10^6 \text{ km.}^2$$

This would reduce the oceanic areas by 2.2 per cent, that is, to

$$352.5 \times 10^6 \text{ km.}^2$$

This reduction of area would cause a corresponding 2.2 per cent increase in the mean depth, that is, an addition of 83.6 meters. The actual rise of sea level would, of course, be somewhat smaller because the area increases as the sea level rises.

It is evident, therefore, that even if the reduction of the earth's surface should assume such dimensions as was assumed above, the resulting rise of sea level would be relatively small, of the same order of magnitude as that produced by deglaciation. But it would be a rise, nevertheless, and as such it would counteract the effect of those forces which cause the regression of the epeiric seas.

Causes of changes in crustal relief. The other difficulty concerns the mechanism by which crustal compression causes the vertical relief between continental surfaces and ocean floors to increase. Such an expression as "collapse of the ocean floor" is quite meaningless when applied to a crust in isostatic equilibrium subject to world-wide crustal compression. But the opposite, a forcing-up of the continents under pressure from all directions, is almost as difficult to picture when we remember how straight and parallel the latest coastal terraces run for very great distances. With a crust as heterogeneous as that of the earth, it seems impossible to force up even a unit much

smaller than a continent without much differential movement within it. It is rather as if the continents and ocean floors became adjusted to a new position of isostatic equilibrium as the earth passes from the condition of crustal tension to that of crustal compression.

It can be shown that this very behavior follows quite inevitably from the conditions of the crust which have been postulated on the basis of other independent observations. These conditions are:

1. The crust is defined as the thin outer shell which differs from the subjacent part of the earth's body in possessing strength (p. 39).
2. It is assumed to be essentially in isostatic equilibrium (p. 39).
3. It is assumed to be subject alternately to stretching and to compression, due to volume changes in the subcrustal depths (p. 141).
4. These volume changes seem to be in some, probably not simple, way connected with corresponding fluctuations in the temperatures of crustal and subcrustal depths (p. 421).

By definition, the bottom of the crust is that level at which the strength of the rock materials becomes very low, approaching zero.

The transition from the crust above to the asthenosphere below cannot be abrupt.[85] The solid crust with high strength must grade into the asthenosphere with low ("residual") strength. As far as isostatic equilibrium is concerned, the properties of a solid of low strength are those of a liquid with high internal friction, with high "viscosity." In order to achieve isostatic adjustment, it is necessary to overcome both the internal friction of the solid crust and that of the viscous asthenosphere.

It is evident that the viscosity of the materials of the asthenosphere determines directly the degree to which isostatic adjustment may approach perfection. Two of the chief factors which control this viscosity are variable under the conditions postulated above. They are: temperature and pressure.

Let us see how changes in these factors affect the viscosity in the upper part of the asthenosphere upon which isostatic adjustments depend largely. A drop in crustal and subcrustal temperatures (postulate 4 above) thickens the crust. The lowering of temperature must

[85] See pp. 38-9.

cause the materials in the upper part of the former transition zone to gain sufficient strength to add them definitely to the crust proper.

But such a drop in crustal and subcrustal temperatures increases not only the thickness of the crust but also its average strength. As the crust grows stronger, more energy is required to overcome the friction within the crust itself. This means that a larger fraction of the total potential energy that is available for the establishment of isostatic equilibrium is spent within the crust. Energy is thus withdrawn from the subcrust, that is, the pressure on the asthenosphere is reduced. Since the subcrustal matter is shrinking at the same time (according to postulate 3 above) the decrease in pressure must be considerable. This must have a decided effect on its viscosity. While more work is required to produce vertical movements within the thickened crust itself, the asthenosphere yields more readily. Isostatic adjustment becomes more delicate.

Conditions are reversed when subcrustal and crustal temperatures rise. Such a rise is assumed to be connected with subcrustal expansion which places the crust under tensional stress. The higher crustal temperatures and the tensional stress decrease the strength of the crust. Vertical adjustments across it become easier and more of its weight bears on the expanding asthenosphere which thus is placed under increased compression. This, however, increases the internal friction within the asthenosphere upon which isostatic adjustments depend primarily. The net result is that the crust becomes less sensitive to deviations from isostatic equilibrium. Peneplanation becomes possible over large portions of the continents making it possible for the seas to transgress readily over large areas.

Another effect of a rise in crustal temperatures and the resulting decrease in the thickness of the crust is of even greater importance. In order to understand this effect picture first the relation of two units of the crust which are in isostatic equilibrium. Let one have an average density 1/10 smaller than the other (2.7 and 3, for instance). The height of the lighter block, then, measured above the base of the crust must be 1/10 greater than that of the heavier one. If, for instance, the surface of the heavier block stood 50 miles above the bottom of the crust, that of the lighter block should extend to a height of 55 miles above the bottom. At the surface, the lighter block

would correspondingly stand 25,000 feet above the level of the heavier block.

If now the crust should grow thinner so that the heavier block would be only 40 miles thick, the lighter block would have to adjust itself so that it would rise 1/10 higher, that is, 44 miles above the bottom of the crust. At the surface, the result would be a decrease of the crustal relief by 5,000 feet.

In epochs of crustal tension, then, isostatic adjustment will not only be less sensitive, but such adjustment as will take place will consist primarily in a decrease of the vertical distance between the surfaces of the largest units involved, the ocean bottoms, and the continental surfaces. The result is a decrease in the capacity of the ocean basins which more than balances the effect of crustal expansion. It causes the oceans to spread across the peneplained continental surface in the familiar way.

The materials which are lost from the base of the crust with rising crustal temperatures should not be thought of as being reduced to the molten state. They merely lose most of their strength and thereby lose, to a large extent, their identity within the materials of the asthenosphere. They merely cease to exert the localized control they had so long as higher strength united them mechanically with the crust above.

The lighter portions derived from higher units may be expected to spread out plastically along the base of the crust to a certain extent. Insofar as their density differs sufficiently from the other materials of the asthenosphere at similar levels, their buoyant effect will not be lost entirely even when they are incorporated in the asthenosphere. It will counteract the change in surface relief described above.

The change in crustal relief actually indicated in the geological record is measured merely by a few hundreds of feet and not by thousands of feet as in the illustration given above. This may be due in part to the smallness of the fluctuations in the thickness of the crust, but it may also be due in part to the presence beneath the crust of such lighter masses.

Later, when crustal temperatures drop again and the uppermost portions of the subcrustal zone reach sufficient strength to become parts of the crust, the local presence of lighter subcrustal materials will cause corresponding vertical adjustments in the opposite sense

from those outlined above. At the beginning of such a period of sub-crustal shrinkage, strong folding takes place in the geosynclinal belts, while the crust is yet relatively thin. As the thickening of the crust proceeds, adjustments add their vertical component to mountain making. The last stages of orogeny consist dominantly of such vertical movements with only subordinated horizontal effects. Simultaneously the peneplained continents rise vertically to an appropriate height. Like the deformation, horizontal and vertical, in the mobile belts, this rise takes place in steps as the accumulating stresses exceed the factors of strength in the crust and in the asthenosphere.

Thus the crustal relief becomes progressively greater in periods of crustal cooling, that is, of crustal shrinkage and compression. This increase is due in part to the increased sensitiveness of isotatic adjustment and partly to the local presence in the uppermost asthenosphere of relatively lighter masses which added to the base of the thickening crust cause local upward adjustments. This applies especially to the mobile belts in which welts were created in the same orogenic epoch. While isostatic adjustments cannot take place so long as the downward expulsion of crustal matter is under way, the welts are raised in the end largely by isostatic adjustment carrying the old erosion surfaces to great heights in the manner so conspicuously exhibited in all the important orogenic belts of latest geologic time.

In this way the same process explains simultaneously the presence of recent terraces on the coasts and of high peneplains on the crests of the young folded mountain belts. It sheds light more especially on what is perhaps the most puzzling aspect of the high peneplains of such orogenic belts as those of our Rocky Mountains. These peneplains have all the appearance of having been lifted vertically, and yet there is often little or no evidence of any tearing along their borders such as would be inevitable if they had been pushed up from an inert, stationary surface. Instead of tearing, increasing evidence is found of compressional forces along their borders or at least of fractureless coherence along the marginal slopes. This is exactly as it should be according to this explanation. Lateral compression and vertical adjustment act simultaneously, as inseparable results of one and the same process.

Later, under conditions of rising subcrustal temperatures and resulting crustal expansion isostatic adjustment would again take place in the opposite sense. The crustal relief would decrease causing the waters of the sea to spread across continental lowlands as described above.

Such a process alone seems adequate to provide the prolonged periodic sinking of such vast regions as that of the interior lowlands of the United States during Pennsylvanian time which made it possible for the coal-bearing formations to accumulate to a thickness of one to several thousand feet. Such piles of sediment require a prolonged sinking of considerable fractions of a continent without important warping to allow the sea again and again to spread in a shallow sheet over the same large areas. Recent studies by J. Marvin Weller, H. R. Wanless,[36] and other members of the Illinoian Geological Survey have shown conclusively that the process of sinking occurred in steps. The result has been a rhythmically repeated sequence of sediments which record alternating transgressions and regressions with the balance in favor of the downward movement of the land with reference to sea level.[37]

Both in the magnitude of the vertical movements and the spacing in time, these Pennsylvanian rhythmic downward movements are comparable to the present-day coastal terraces. Most, if not all, coastal terraces likewise seem to record an alternation of positive and negative movements of the strand line, only here the net result has been directed upward instead of downward. They also affect large parts of a continent without much warping.

Thus, without the need of auxiliary hypotheses, assumptions based originally on entirely independent observations lead logically to an explanation of the large eustatic movements of sea level with reference to the continents and of the quite universal differential vertical uplifts

[36] J. Marvin Weller, "The Conception of Cyclical Sedimentation during the Pennsylvanian Period," *Illinois Geol. Survey, Bull. 60,* 1931, pp. 163-77; H. R. Wanless, "Pennsylvanian Cycles in Western Illinois," *ibid.*, pp. 179-93, esp. Fig. 46, p. 192.

[37] In western Illinois, individual cycles of sediments within the Pennsylvanian are separated by erosion surfaces showing a relief as high as 80 to 100 feet in two cases. The regressions thus indicated may be due in part or wholly to climatic changes in the level of the sea.

of peneplains in young orogenic belts. We may summarize this far-reaching interpretation as follows:

Opinion 38. The essentially radial (vertical) movements which increase the total relief on the earth during periods of crustal compression and decrease it during periods of crustal tension result from the isostatic adjustment of crustal units of different densities to changes in the viscosity of the upper asthenosphere and in the thickness of the crust, changes such as must follow inevitably any rise or fall in subcrustal temperatures in connection with subcrustal volume changes.

The thought that the Pleistocene and present exhibit a higher degree of isostatic compensation than has been customary through the periods of quiet which separate orogenic epochs, was expressed as long as two decades ago by Bailey Willis. Barrell[88] took it up and suggested that "presumably a decrease of density within the zone of isostatic compensation has taken place . . . during the Cenozoic and the uplift has accompanied or followed the internal change."

The writer arrived independently at the conclusion expressed above. Change in density and change in viscosity may well amount to the same thing under the conditions of pressure existing in the asthenosphere.

A similar view concerning the nature of the larger vertical movements of the crust was advanced by Joly in 1923.[89] But Joly's reasoning is based on Airy's concept of "roots of mountains" and of floating continents. He thinks in terms of a melting and freezing of the basaltic substratum and of consequent variations in the buoyancy of the immersed masses. We have seen that the premises for Joly's reasoning are untenable. But his central thought that isostatic adjustment is fundamentally controlled by subcrustal thermal conditions is independent of his specific premises. He has focused attention on this basic idea by boldly working out its logical consequences. Whether he was justified in tying it to the rôle which radioactive substances play in the thermal life of our planet remains to be seen.

[88] J. Barrell, "The Strength of the Earth's Crust," *Jour. Geol.*, Vol. 22, 1914, p. 35. (See also p. 291.)

[89] J. Joly, "Movements of the Earth's Surface Crust," *Philos. Mag.*, Vol. 45, 1923, pp. 1167-88; Vol. 46, 1923, pp. 170-6. See also J. Joly, *Surface History of the Earth*, Oxford, 1925.

5. Swells and Basins

Paleozoic platform of eastern United States. The preceding discussion dealt with the major changes in crustal relief which exert a world-wide control on the eustatic movements of the sea and on the broader relief of the continents. From this largest aspect of epeirogenic deformation we now pass on to one of its details.

Just as the continental and oceanic areas appear as vast swells and basins, so each of these in turn is subdivided into similar non-linear elements. In the eastern United States, which has remained essentially free from orogenic movements since Jurassic times, the geological map shows a well defined system of swells and basins. In 1910, Ruedemann published a paper "On the Symmetric Arrangement in the Elements of the Paleozoic Platform of North America" from which Fig. 96[40] is here reproduced. The Wisconsin pre-Cambrian area (D_2) and the Adirondacks (E_2) represent two swells which are really southern prongs of the Canadian shield (A), each, however, more or less separated from it by a depression (D_1 and E_1). The cross-hatched areas (B_2, B_3, B_4) show the three large basins, which still retain the Pennsylvanian rocks. The Ozark uplift (D_3), and the Cincinnati and Nashville "domes" (B_1) are typical "swells."

Heavy dashed lines show Ruedemann's interpretation of the pattern. Note that the eastern line E_2-E_3, leads from the non-linear swell of the Adirondacks to the linear element of the crystalline Appalachians. This is objectionable so far as we separate swells and basins logically from welts and furrows. It suggests, however, that here a swell was changed into a welt in the course of Appalachian orogeny.

Africa. For another illustration of swells and basins we turn to the continent of Africa. Fig. 97[41] is taken from Krenkel's book on the geology of Africa. The hachured areas represent basins of the present surface, both of the continent and of the ocean floor. On the continent, the four largest areas represent the Chad, Ghazal, Congo, and Kalahari basins. Krenkel attempts also to show a symmetry, a definite trellis pattern of diagonal swells which extends far beyond

[40] Reproduced from R. Ruedemann, "On the Symmetric Arrangement in the Elements of the Paleozoic Platform of North America," *N.Y. State Mus., Bull. 140*, 1910, Chart I, opp. p. 142.

[41] Reproduced from E. Krenkel, *Geologie Afrikas*, I. Teil, Berlin, 1925, Fig. 4, p. 26.

the borders of the continent. For obvious reasons, he calls the northeast trending lines the Somalic, those trending northwest the Eryth-

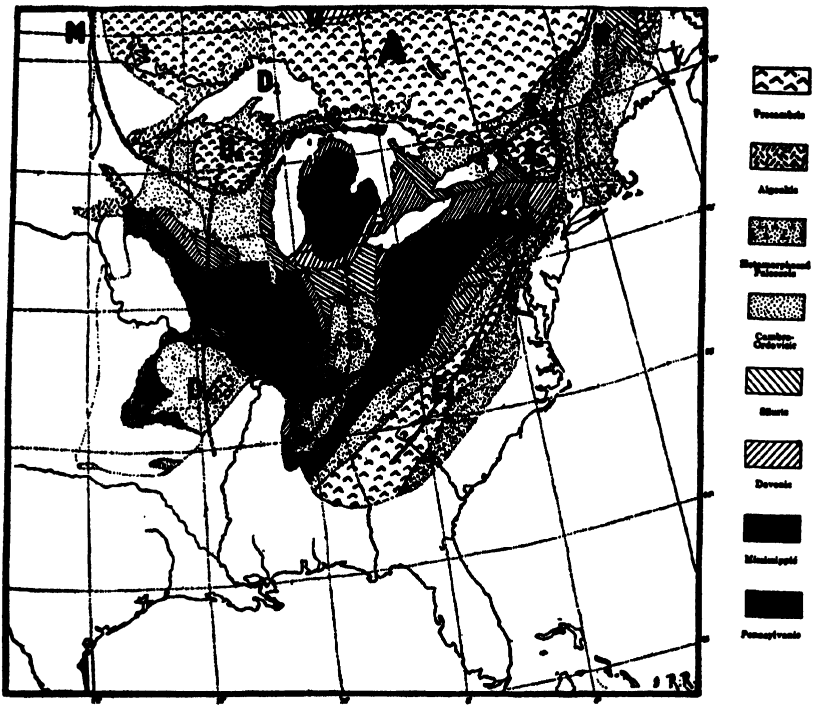


Fig. 96. Geologic sketch map of the eastern United States, showing Ruedemann's interpretation of the grouping of major units.
(R. Ruedemann, 1910)

reic system. He sees in them directions which have guided the development of the continent since pre-Cambrian times.

To what extent these inferences concerning innate symmetries in the distribution of swells and basins correspond to something real in nature is difficult to judge. In both regions, the eastern United States and in central and south Africa, there seems to be a tendency toward a quincunxial arrangement of swells and basins, indicated by the grouping of B_2, B_3, and B_4 on Ruedemann's map and of the Chad, Ghazal, and Congo basins on that of Africa. But even these groupings may be merely accidental.

Krenkel's map shows clearly that the same pattern of basins and swells which characterizes the continental platforms outside the mo-

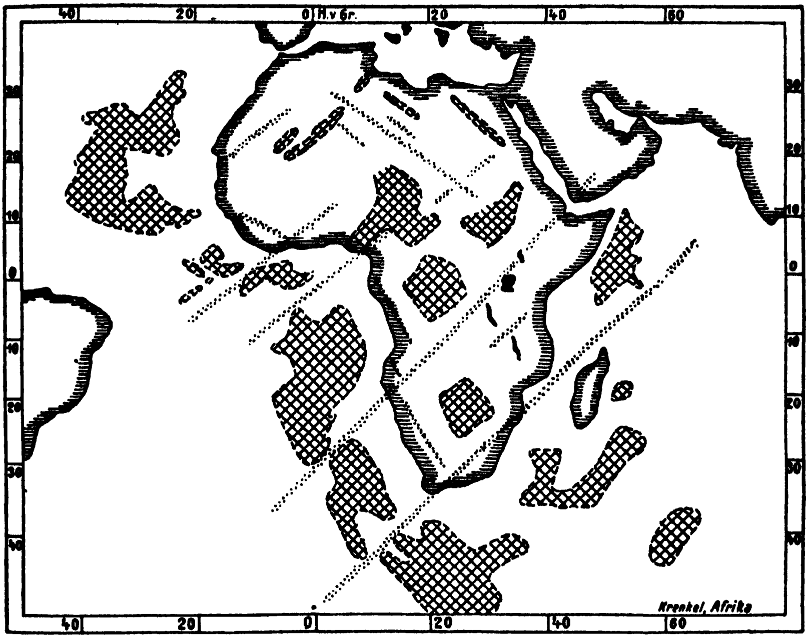


Fig. 97. Diagrammatic map of Africa showing the distribution of basins (cross-hatched) on the continent and on the floors of the adjoining oceans.

(E. Krenkel, 1925; reproduced from *Die Bruchzonen Ostafrikas*, by permission of Verlagsbuchhandlung Gebrüder Borntraeger)

bile belts, also dominates the vast stretches of ocean floor between mobile belts. This relation is important enough to be formulated as a law.

Law 46. Swells and basins similar in form and dimensions exist at the level of the ocean bottoms as well as on the continental platforms.

This law parallels exactly law 6. It corroborates the conclusion reached in the discussion of law 6 that in their mechanical behavior those portions of the globe which are covered by the ocean do not differ in any significant way from those which today are land.

In the absence of specific clues, we cannot venture to formulate definite ideas as to the mechanism that underlies these non-linear deformations of the crust. They seem to represent the manner in which

the crust outside the mobile belts reacts to the alternating periods of crustal tension and compression. But why they assume the shapes and groupings they do, we are not prepared at present to say.

Swells and deep-seated intrusions. Emmons has recently published arguments to show that the sulphide ores of the Mississippi Valley have originated from "deep-seated igneous masses of which the basic and acid rocks of the region are upward extensions."[42] His arguments are not necessarily convincing, however, and the age relations of the intrusives to the ore deposits are uncertain. But the presence of acid igneous materials within the Paleozoic platform, far from orogenic belts, is in itself interesting. One is the coarse pegmatite dike on the Camden-Laclede County line, near Decaturville, in Missouri, which was described long ago by Winslow.[43] The other is the granite of the Rose Dome in Woodson County, Kansas, which shows definite contact metamorphism extending to a distance of 15 inches from the contact.[44]

In the case of the first, the actual outcrop does not exceed a few square yards, and the Rose Dome locality covers only about one hundred acres. They are probably the extreme acid differentiates of basic intrusives such as occur normally in the interior plateaus.

But we gain relatively little by the recognition that intrusives are involved in the deformation of the crust outside of the mobile belts. We have learned to recognize intrusives as symptoms of deformation of the crust, not as causes.

Basins and deep-seated intrusions. Barrell's views on the relation between regional subsidence and basic intrusions were published posthumously.[45] They are based on the saucer-shaped form, with the concave side upward, of many basic intrusive bodies, the "lopoliths" of Grout.[46] They are in principle identical with the explanation the

[42] W. H. Emmons, "The Origin of the Deposits of Sulphide Ores of the Mississippi Valley," *Econ. Geology,* Vol. 24, 1929, pp. 221-71 (quotation from p. 271).

[43] A. Winslow, "Lead and Zinc Deposits, Part 2," *Missouri Geol. Survey,* Vol. 7, 1894, pp. 432-3.

[44] W. H. Twenhofel, *Bull. Geol. Soc. America,* Vol. 37, 1926, pp. 403-12; W. H. Twenhofel and B. Bremer, "An Extension of the Rose Dome Intrusive, Kansas," *Bull. Am. Assoc. Petrol. Geol.,* Vol. 12, 1928, pp. 757-62.

[45] J. Barrell, "On Continental Fragmentation and the Geologic Bearing of the Moon's Surficial Features," *Am. Jour. Sci.,* 5th ser., Vol. 13, 1927, pp. 283-314.

[46] F. F. Grout, "The Lopolith; an Igneous Form Exemplified by the Duluth Gabbro," *Am. Jour. Sci.,* 4th ser., Vol. 46, 1918, pp. 516-22.

writer developed for the sinking of furrows, but applied areally. "Great intrusions of basic magmas rising from the deeper asthenosphere would, under the principles of isostasy, produce subsidence," he writes. The principle is in harmony with Washington's law (p. 44).

Barrell's paper is especially valuable because of the way it connects the formation of basins to the phenomenon of continental fragmentation. It provides the mechanism for carrying to oceanic depths parts of the crust which had held continental elevations for long periods.

But neither Barrell nor Suess, who voiced similar views, have been able to give a satisfactory reason for the tendency of swells to assume a circular shape, or for their grouping.

We can gain little by pushing speculations further. We must be content at present to see in these forms the expression of the deformation of the crust outside of mobile belts.

6. Similarities and Parallelisms in Opposite Shore Lines

It is fitting that at the end of this discussion we return once more to the larger lines on the face of the earth. We began our studies by noting the presence of linear elements of structure in contrast to non-linear elements. The pattern of these linear elements, the mobile belts, occupied a central place in our considerations.

We now turn to the lines which bound conspicuous non-linear units of the earth's surface, such as continents and larger islands. They attracted attention and caused speculation at an early date, and lately they have occupied a central place in the reasoning of many men. The continental outlines on opposite sides of the Atlantic Ocean are singular in dimensions and degree of correspondence. Fig. 98,[47] taken from an interesting paper by Pickering, published in 1907, serves well to show the existing relations. On each side of the Atlantic, six corresponding points are marked by circles and connected by straight lines, which serve as reference lines. A dotted line drawn west of the western reference line marks those parts of the outline of the eastern continents which extend beyond it.

In the paper from which this figure is taken, Pickering, the astronomer, shows that if G. H. Darwin's view (1879) is correct, that the

[47] Reproduced from W. H. Pickering, "The Place of Origin of the Moon—The Volcanic Problem," *Jour. Geol.*, Vol. 15, 1907, Fig. 4, p. 29.

Fig. 98. Map of the Atlantic and Polar Oceans, showing six pairs of corresponding points on opposite sides of the ocean. For South America an additional set of corresponding points is shown rotated with reference to the primary points.
(W. H. Pickering, 1907)

moon's mass was torn from the body of the earth by the centrifugal force of accelerated rotation, the Pacific Ocean must represent the scar left by this operation on the earth's crust. He writes: "When the moon separated from us, three-quarters of this crust was carried away, and it is suggested that the remainder was torn in two to form the eastern and western continents. These then floated on the liquid surface like two large ice-floes."[48]

In 1910, "The first notion of the displacement of continents" came to Wegener "when, on studying the map of the world, [he] was impressed by the congruency of both sides of the Atlantic coasts."[49] In the same year, Taylor published the first of a number of papers in which he assumes large horizontal movements of continental masses. His reasoning grew, however, from a contemplation of Suess' picture of the great belt of Tertiary mountain folding. If such folding meant horizontal movement, there should be evidence of it in the form of tearing away on the other side of the moving masses. Looking at the western half of the earth, he was impressed with the "rift valleys," as he called them, which separate Greenland from the North American continent. Fig. 99,[50] taken from a later paper, shows his interpretation of this interesting region. The arrows indicate the assumed direction of "crustal creep" and the lines marked *AA*, *BB*, etc., show the supposed distance of movement.

There can be no doubt that, granting minor changes due to subsidiary factors, the hypothesis of horizontal drift is sufficient to explain these rather striking features. The question is, however, not merely whether this hypothesis is sufficient, but whether it is necessary.

In order to find a basis for an opinion on this point, turn to a third actual example. In Fig. 100[51] the letters *a* and *a'*, *b* and *b'*, mark congruent portions of shore lines of islands and a "mainland." Here, as on Taylor's map, the arrows mark the direction of supposed drift. Note especially the way the island marked *a'* was displaced in a direction parallel to the shore line north of *a*, in a manner exactly com-

[48] W. H. Pickering, *op. cit.*, p. 30.

[49] A. Wegener, *The Origin of Continents and Oceans*, trans. from the third German edition, New York, 1924, p. 5.

[50] Reproduced from F. B. Taylor, "North America and Asia; A Comparison in Tertiary Diastrophism," *Bull. Geol. Soc. America*, Vol. 39, 1928, p. 988, Fig. 1 (on p. 985, a bibliography of Taylor's papers on this subject).

[51] Drawn from the colored *Relief Map* of the United States, published by the U.S. Geological Survey, on the scale 1:7,000,000 (edition of November 1911).

parable to the assumed movement of Grant Land and Ellsmere Land along the northwest coast of Greenland. The narrow strait just west

Fig. 99. Map of Greenland and adjacent parts of North America showing Taylor's interpretation of the development of the present configuration through continental drift.
(F. B. Taylor, 1928)

of the letter *a'* is the exact counterpart of the "offsetting rift" which cuts across the northern end of Greenland according to Taylor's interpretation.

This region is not now covered by the sea. It shows the United States east of the 102nd meridian as it would look if it were sub-

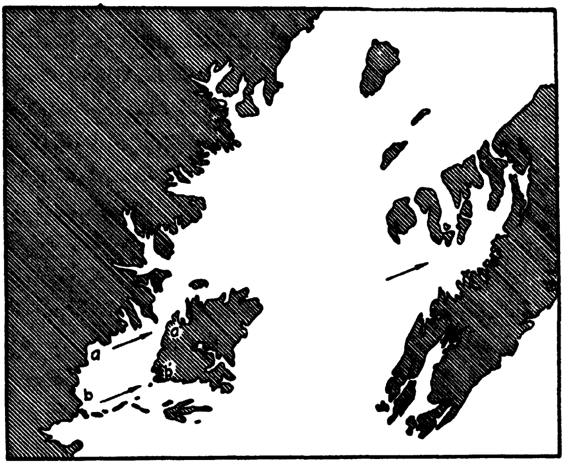


Fig. 100. Map of the central United States from the Allegheny plateau to the Great Plains with all land above the 1,000-foot contour shaded. If the blank area represented the sea, the map picture might be interpreted as the result of continental drift, as indicated by the arrows. Note that opposing shores tend to be parallel.

merged beneath sea level to a depth of one thousand feet. The outlines of the islands represent the 1000-foot contour line. The island at *a'* is formed by the Ozark plateaus, with the Ouachita Mountains on the south side; islands mark also the western edge of the eastern plateaus in Indiana and in east central Tennessee. The northernmost islands are formed by the highest areas on the southern peninsula of Michigan. The shore of the "mainland" follows approximately the eastern edge of the Great Plains.

This little map contains food for useful thought. The correspondence of curvatures and dimensions on opposite shore lines is quite as striking as in the case of Greenland with which this region corresponds somewhat in scale. The outlines are notably straight and angular. Wave-cutting prolonged through geological periods would make them more so, strongly suggesting faulting.

Yet one thing is certain: There was no "drifting" in the case of these "islands." There may not have been any in the case of Green-

land. The hypothesis of drift is not necessary to account for the pattern of opposed shore lines in continents and islands. Since it is contrary to other facts, we have long before refused to accept it.

What, then, is the cause of the observed parallelisms? As in the case of the swells and basins, no simple answer is available at present. While the outlines of the "islands" in Fig. 100 are obviously, at present, largely determined by the limits to which subaerial erosion has progressed, these limits depend ultimately on the pattern into which the crustal surface was bent. This pattern is influenced by the "grain" of the upper part of the crust and by fracture systems, as well as by the general distribution of stresses within the crust.

Ever since Daubrée's experiments and accompanying discussions,[52] much has been written on repeating patterns in the configurations of the earth's surface. The reader not familiar with the larger aspects of fracture patterns should turn to a good map of the island of Crete, for example. The east-west striking shores of the island are offset repeatedly by north-south fractures. These fracture lines, moreover, are spaced at sensibly similar intervals forming at least two systems, the spacing of one of which is a simple multiple of that of the other.

The same system reappears in the western part of Asia Minor. Similarly, the northwest-trending fractures which divide the Paleozoic substructure of western Europe into blocks with parallel outlines, show a certain tendency at uniform spacing. One cannot look at a good topographic map of Nevada without getting the impression that the spacing of the mountain ranges approximates a definite pattern. But we are still far from being able to evaluate correctly the mechanical significance of earth "lineaments."[53] Attempts to interpret regularities and similarities in the distribution of lines, angles, and arcs on the face of the earth, so far as they are not sharply defined struc-

[52] A. Daubrée, *Etudes synthétiques de géologie expérimentale,* Paris, 1879. (Note esp. Pls. II to VII.)

[53] "While believing that the greater number of rectilinear features have their origin either in planes of jointing or in faulting, there appears to be no advantage, but serious disadvantage, in giving this implication to the term. The term as here used is nothing more than a generally rectilinear earth feature." W. H. Hobbs, "Lineaments of the Atlantic Border Region." *Bull. Geol. Soc. America,* Vol. 15, 1904, p. 485n.

turally, seem as premature today as in 1852, when Elie de Beaumont thought he could fit the main lines into a pentagonal network of 120 equal rectangular triangles.[54] All we can say is that there are indications in all parts of the world of tendencies toward parallelisms and similarities in curvature and angular relations which must involve fundamental properties of the crust. What is known so far is too fragmentary to allow us to go further at the present.

The hypothesis of continental drift gave promise of offering a solution for three difficult problems: (1) the excessive shortening that seemed indicated in the structure of Alpine mountain chains; (2) the correspondences in the configuration of opposite shores of continents and islands; and (3) the extraordinary distribution of ice during the Permian glaciation. For the first two items we have found that the facts do not demand continental drift for an explanation. Since it is incompatible with other observations which are just as definite, the writer finds it impossible to accept this simple explanation although he can do little more than indicate the direction from which ultimately a satisfactory understanding may be expected.

The third consideration, the strange distribution of ice during Permian glaciation, is not concerned with the structural properties of the crust.

It enters as an argument only if it can be definitely proved that the grouping of ice masses in the Permian cannot possibly be explained in terms of the known physics of the air in its effect on the topography of Permian time, more especially the distribution of land and sea and elevation above sea level.

It is doubtful if knowledge in either of these two fields of observation is sufficient at present to permit any definite statement. The geologist is apt to be aware of this lack of accurate knowledge more in his own field than in that of meteorology and climatology. Yet he cannot help being surprised when he learns that, during the Pleistocene, gla-

[54] Yet it is well worth while to "play" with parallelisms and similarities among structural and topographic features. Many important advances of knowledge have had their beginning in such "play." From this point of view Deeke's papers on this subject are worth reading and trying out on large maps or, better still, a large globe. W. Deeke, "Ein Grundgesetz der Gebirgsbildung?," *N. Jahrb. f. Min.*, etc., 1908, I, pp. 119-33; II, pp. 33-48, 56-68; 1910, I, pp. 118-39.

ciers reached down to an elevation of less than 5,000 feet[55] above sea level on Mt. Ruwenzori, almost exactly on the Equator, on the border between Uganda and the Belgian Congo. The present glaciers end at an elevation of 13,450 feet. The snow line lies at a height of 14,760 feet above sea level.[56]

Volcanic Kilima Njaro, 3° south of the Equator, on the borders of Tanganyika territory, with a height of 19,320 feet and a present limit of glaciers at 13,650 feet, had glaciers during Pleistocene time which extended to 4,870 feet above sea level.[57] Sixty degrees farther north, on the southern slope of the St. Elias Range, the snow line lies at an elevation of about 2,500 feet. The glaciers flowing down from this snow line to the flat lowland at the foot of the mountains form the piedmont ice sheet of Malaspina glacier. There it covers an area of approximately 1,500 square miles[58] in country with a mean annual temperature around 40° F.[59] The writer wonders what would have been the condition at Ruwenzori if a broad upland had existed about its base at an elevation sufficiently high to be cold enough to receive the greatly increased precipitation[60] in the form of snow. The ice would have gathered into the form of a piedmont glacier. One then wonders what effect the presence of a large piedmont glacier would have had on an air circulation which under present conditions wraps the high mountain tops daily in rain-giving clouds.

[55] Roccati gives the lowest limit of the ice as having been 4,600 feet. (A. Roccati, "Nell' Uganda nella Catana del Ruwenzori," *Boll. Soc. Geol. Italiana*, Vol. 26, 1907, pp. 127-58. "I Minerale utili dell' Uganda," *ibid.*, Vol. 28, 1909, pp. 23-63). First described by G. F. Scott Elliot (G. F. Scott Elliot and J. W. Gregory, "The Geology of Mount Ruwenzori and Some Adjoining Regions of Equatorial Africa," *Quart. Jour. Geol. Soc.*, Vol. 51, 1895, pp. 669-80). Quoted from J. W. Gregory, *The Rift Valleys and Geology of East Africa*, London, 1921, p. 265.

[56] Quoted from E. Krenkel, *Geologie Afrikas*, 1. Teil, Berlin, 1925, p. 261. ("4,500 meters," according to Krenkel, who uses round figures, glaciers end "300 meters" lower, which would place the lower end at 13,780 feet.)

[57] C. E. P. Brooks, *The Evolution of Climate*, 2nd ed., New York, 1925, p. 103.

[58] I. C. Russell, "Malaspina Glacier," *Jour. Geol.*, Vol. 1, 1890, pp. 219-45.

[59] Juneau, Alaska, lat. 58°18′ N., long. 134°24′ W., mean annual temp. 42°+F.; Valdez, Alaska, lat. 61°7′ N., long. 146°16′ W., mean annual temp. 35°+. From H. H. Clayton, "World Weather Records," *Smithsonian Misc. Coll.*, Vol. 79, 1927, pp. 698 and 716.

[60] Brooks gives convincing evidence that it was a great increase in precipitation and not a great lowering of the snow line that caused the great lengthening of the Pleistocene glaciers. *op. cit.*, p. 104.

In New South Wales the Permian ice reached sea level at as low a latitude as about 35° S. But only 8° farther south, in New Zealand, the glaciers reached below the present sea level in Pleistocene time. "In the Te Anan and Wakatipu basins, where now no glaciers exist, there were then streams of ice seventy miles long. The western fiords which radiate from mountains where now there are but few patches of permanent snow were filled with huge ice masses."[61]

New Zealand may have had a greater elevation during Pleistocene time. But there are limits to the assumptions of vertical movements. Brooks states that Neuhauss discovered "giant erratics, scratched and polished, and moraines at *sea level* at the western end of Huon Gulf, New Guinea."

He continues: "The region is very unstable, and is known to have stood at a very much higher level, perhaps 10,000 feet or more, in Quaternary times, and if the moraines indicate glaciers terminating at 10,000 feet above the sea they are explicable by a slight fall of temperature and increase of snow fall."[62]

Not being familiar with the geology of New Guinea, all the writer can say is that a portion of the Tertiary mobile belt which was depressed 10,000 feet in Pleistocene time would be to him almost as unexpected an object as a Pleistocene glacial moraine at sea level 7° south of the Equator. He suspects that so large a downward movement was assumed to account for the presence of the moraines. The writer, on the other hand, is again impressed with the coincidence of these traces of glacial effects at low altitudes with a relatively low present snow line and with a region of almost perpetual rain at greater heights. On the south side of Wilhelmina Peak, in the Orange ("Snow") Mountains, in the northwestern part of the island, the permanent snow fields ("névés") extend down to a level of 13,000 feet (4,000 meters).[63]

These scraps of information are here quoted merely for one purpose: to show that there are features of Pleistocene glaciation which to the layman in meteorology seem to point to a grouping of climatic factors in Pleistocene time which, coupled with sufficient altitude, go

[61] P. Marshall, "New Zealand," *Handbuch d. regionalen Geologie,* Heft 5, Heidelberg, 1911, p. 49. See esp. the map, Fig. 13, p. 48.

[62] C. E. P. Brooks, *The Evolution of Climate,* 2nd ed., New York, 1925, p. 111.

[63] P. Privat-Deschanel, "Océanie," in *Géographie Universelle,* Paris, 1930, p. 234. (See photo. on Pl. XLV, opp. p. 238.)

a long ways toward accounting for the conditions during the time of Permian glaciation.[64] So far as the writer knows, there exists no monographic treatment of this phase of low-latitude Pleistocene climate, written by a competent meteorologist and based on a detailed analysis of the present climatic conditions. We will do well to await such studies before we demand a drifting of continents to get the ice where we need it.

In the work quoted above, Brooks expresses the opinion that the peculiar distribution of the Permian glaciation may make it necessary to assume a position of the South Pole different from that of today, possibly somewhere southeast of South Africa. If Wegener's hypothesis of continental drift solved the climatic problem of Permian glaciation merely by assembling the continents into a single land mass, it would commend itself more. But Wegener requires, in addition to his highly speculative continental drift, also an equally speculative shift of the poles.[65]

Whatever the ultimate verdict may be concerning Wegener's and Köppen's views, they cannot be considered sufficiently well founded at present to be effective as an argument in favor of the assumption of a former contact of continents along similar opposite shores.

7. The General Shape and Grouping of the Continents

If there has been no drifting of continents, at least since the beginning of the geologic record, the general shape of the continents and their grouping on the globe require explanation. At first glance the disposition of the continental masses on the earth seems quite fortuitous. Closer inspection discloses, however, several properties which deserve attention.

1. One continent centers about the South Pole.
2. Six non-polar continents are grouped into three pairs, each pair lined up so as to form an elongated land mass of roughly meridional orientation.
3. Each pair is much wider at the northern than at the southern end.

[64] See, e.g., E. Huntington, "The Solar Hypothesis of Climatic Changes," *Bull. Geol. Soc. America,* Vol. 25, 1914, pp. 578-88.

[65] W. Köppen and A. Wegener, *Die Klimate der geologischen Vorzeit,* Berlin, 1924.

4. The three continents on the northern hemisphere are arranged in such a way as to form a nearly continuous belt of land in 60° N. latitude.
5. There is a distinct tendency toward an antipodal relation between continental and oceanic areas.

The last property does not hold good for all parts of the land surface and in view of the dominance of water on the earth's surface is of least significance. Yet it is sufficiently pronounced to deserve attention.[66] Thus, the land ring of 60° N. latitude has its counterpart in the oceanic ring at 60° S. latitude. The land mass of Antarctica lies opposite the deep sea of the North Pole. North America corresponds remarkably closely to the Indian Ocean. Africa, central, and eastern Asia are antipodal to the southern and central Pacific. Australia lies nearly opposite the Atlantic basin north of the Equator. In spite of all its irregularities and exceptions,[67] the general pattern suggests a tendency which may result from the action of a general law.

The law may be that first suggested by Green and generally known as the tetrahedron hypothesis.[68] Of all regular bodies with a given surface, the sphere has the greatest and the tetrahedron the smallest volume. A shrinking sphere with an inert surface may, therefore, tend to assume the form of a tetrahedron. An expanding tetrahedron, on the other hand, may tend toward the shape of a sphere. If this were to apply to the earth, the spheroid might be expected to tend to become a "tetrahedroid." Since the earth deviates only slightly from the shape of a sphere, the change in the direction of a tetrahedroid cannot be more than merely a slight tendency for parts of the crust

[66] See the little map in J. W. Gregory, "The Plan of the Earth and Its Causes," *Am. Geologist*, Vol. 27, 1901, p. 104.

[67] Exceptions are: Southern South America opposite southeastern Asia; Graham Land opposite Taimyr peninsula; Victoria and Wilkesland opposite Greenland and the North American Arctic archipelago. Yet only 1/20 of all the land surface of the earth lies antipodal to land. (Th. Arldt, *Die Entwickelung der Kontinente und ihrer Lebewelt*, Leipzig, 1907, p. 526.)

[68] Green's original paper is not generally accessible: Lowthian Green, *Vestiges of the Molten Globe as Exhibited in the Figure of the Earth's Volcanic Action and Physiography*, Part I, London, 1875. Part II, *The Earth's Surface Features and Volcanic Phenomena*, Honolulu, 1887; J. W. Gregory, "The Plan of the Earth and Its Causes," *Am. Geologist*, Vol. 27, 1901, pp. 100-19, 134-47. Especially Th. Arldt, *Die Entwickelung der Kontinente und ihrer Lebewelt*, Leipzig, 1907, pp. 521-41.

to move closer toward the earth's center, corresponding to what ultimately would be the tetrahedral faces, while others tend to remain more distant, corresponding to the ultimate position of the edges. The former would correspond to the ocean basins, the latter to the main axes of the continental masses.

The result should be an arrangement which distinctly resembles that existing on the earth: If we picture the ultimate tetrahedron in such a way that one corner points downward, corresponding to the South Pole, we have a face at the opposite pole surrounded by three edges, which would be foreshadowed by the land ring of the northern hemisphere. The three edges running down to the South Pole would be suggested by the three roughly meridional lines running through the three pairs of continents: North and South America; Europe and Africa; Asia and Australia. The three great ocean basins which extend northward between the continents would occupy the places of three tetrahedral faces with the Arctic Ocean as a mere rudiment of the fourth. The writer considers it possible that such a vague tendency toward a tetrahedroid distribution of masses arises in the process of crustal deformation as he has pictured it. This tendency, like the development of mobile zones, would be a function of the strength of the earth's crust, forcing a pattern on the earth's surface against the levelling tendency of its isostatic condition.

According to the view here developed, the mobile zones originate as fracture zones under crustal tension. When the crust begins to suffer compression, overthrusting and folding become localized along these mobile belts, taking up the horizontal shortening of the circumference. As shrinking progresses the crust as here defined thickens to the extent that cooling is involved. The thickening of the crust results in an increase of crustal relief (p. 446). This must involve a considerable amount of lateral transfer of matter below the crust.

If the crust had no strength and if, therefore, there were no tendency in the crust as a whole to deviate from a spheroidal shape, the relatively light material forced into subcrustal space in the course of crustal compression might be expected to flatten out in such a way as to form ultimately a layer of uniform thickness beneath the crust. If, on the other hand, the crust behaved essentially as an inert, relatively strong, skin adapting itself to the shrinking subcrustal body, its tendency toward a tetrahedral shape might cause the lighter materials

in the upper part of the asthenosphere to become localized along those portions of the surface which lie between the centers of the faces of the foreshadowed tetrahedron where a deficiency in pressure would exist. The centers would thereby be depressed even more than the purely isostatic effect of cooling and thickening of the crust would demand and the surface between them would be elevated correspondingly more. The writer suggests that in this way the tendency toward tetrahedral distribution of high and low areas finds its weak expression.

Some such control seems indicated by the distribution of the present continental areas when viewed in their relation to the present orogenic belts. The reader should turn to Fig. 23 (p. 91), which shows the hypothetical pattern of mobile belts.[69]

In order to bring out the peculiar relation to which the writer wishes to call attention, it is necessary to review the plan of the present pattern of mobile belts as shown in these two figures. The "cross" consists of four arms: the Mediterranean, the Ural, the Malaysian, and the largely hypothetical Mozambique arm. Each of these arms runs nearly straight for a distance, then bends more or less abruptly and finally runs into the circum-Pacific "ring."

These relations may best be visualized by laying strips of moistened tissue paper on a small globe to mark the "mobile belts." Such a globe, or the figures here referred to, show readily the following relations: All four angles at the center of the cross are occupied by land masses; all other larger land masses lie along the Pacific "ring," and all of them on its outside, with not one lying within. The latter relation is particularly remarkable. It is as if the present location of the continents were somehow controlled in part by their relation to the mobile belts with a vague tendency toward a symmetrical distribution with reference to their pattern.

The chief irregularity of the figure arises from the disproportionate smallness of the sector enclosed by the Himalayan and Ural-Verkhoyansk arms. Analogy with the other corresponding areas would demand a distance between the Pamirs and Japan twice or three times as long as that actually existing. The center of this space should be occupied by an oceanic area, about where southeastern Asia now

[69] See also Fig. 1, p. 25, of W. H. Pickering, "The Place of Origin of the Moon," *Jour. Geol.*, Vol. 15, 1907.

lies. Curiously enough, this is precisely the region which forms the only large exception to the tendency toward antipodal positions of land masses and oceans; the southern half of South America lies antipodal with reference to precisely this space which by analogy to the other areas embraced between the arms of the "cross" would be occupied by the sea if the pattern of the mobile belts had achieved greater symmetry.

To what extent these relations are of intrinsic significance cannot be known at present. Perhaps they are purely accidental and devoid of meaning. It seems equally possible, however, that they are the result of the interplay of the three fundamental factors indicated above. To the writer this seems at present a reasonable interpretation.

Opinion 39. The general shape and grouping of the land masses on the earth is the result of the interplay of three factors: (a) The physical nature of the crust, which possesses strength in contrast to the subcrustal asthenosphere which reacts to all stress differences by viscous flow, resulting in the isostatic behavior of the crust; (b) the presence of mobile zones which take up most of the stresses resulting from subcrustal expansion or contraction; (c) the tendency of the relatively strong inert crust to assume a tetrahedroid shape when the subcrustal volume diminishes.

In such vague notions ends our investigation. They are vague because the data on which we can base our reasoning are inadequate. If we had dozens or hundreds of earth-like bodies within reach of our telescopes we could hope from the comparative study of so many faces to find the laws that govern their physiognomy. Since the face of the earth remains unique to us, we can only hope to understand its meaning by analyzing its traits one by one, trying to grasp the mechanical meaning of each, progressing by small steps, where we can go from verifiable fact to sound conclusion, content to contemplate from afar the outlines of the goal.

CHAPTER XIV

SUMMARY AND SYNTHESIS

"A man that cometh to a cross-roads must turn his back upon the one way to follow the other."
Edna St. Vincent Millay, in *The King's Henchman.*

Having reached the end of a long and tortuous path of reasoning, we must look back over the route traversed to sum up what we have found. Analysis has yielded us a series of laws. They are listed at the end of this book as the main product of this investigation. The future must show if they correspond to reality and, therefore, can be used as a safe basis for reasoning. Accepting them as such for the present, we have gone beyond them and ventured tentative interpretations.

The reader is invited again, as in the foreword, first of all to test the soundness of the laws by his own field experience, and then to devise other, perhaps better, interpretations which will be consistent with all. The synthesis of his own interpretations will yield each reader such satisfaction as is possible at the present undeveloped state of geological knowledge.

In summing up the laws and his personal interpretations given in this volume, the writer presents such a synthesis as a possible picture of diastrophism which seems to him consistent with all known facts of geology and geodesy and not in conflict with the broader laws of the fundamental sciences.

In reading the following pages, the reader should refer constantly to the list of laws which ends the book (pp. 490-5). For the opinions expressed the reader is referred to the page in the book on which the opinion was formulated. In the text, the observations which form the basis for the "laws" and "opinions" are stated elaborately and great care is taken to distinguish between facts, inferences, and hypothetical assumptions. When in doubt about the basis for any statement made in this summary, the reader should refer back to the text.

1. The Crust

The earth's surface is not that of a nearly perfect spheroid. It is molded into linear and non-linear (law 3, p. 4) elevations and de-

pressions (law 1, p. 1) by forces from within. This book contains an inquiry into the nature of these forces and their mode of action.

The definite relation between elevation and density, known as isostasy (law 9, p. 25) indicates the existence of some sort of equilibrium between crustal units of limited dimensions. This equilibrium might be that of a stronger material immersed in a weaker one, or that of materials of comparable strength but varying density resting on a yielding support.

Two observations especially lead to the second alternative and render the first impossible:

(1) Both linear and non-linear crustal surface forms (law 3), comparable in shape and dimensions, occur on ocean bottoms as well as on continental platforms (laws 6 and 45, pp. 14 and 441). This proves that no significant difference exists in the behavior of ocean floors and continents under the action of long-continued crustal stresses (opinion 1, p. 14).

(2) Acid materials melt at so much lower temperatures than the more basic ones (pp. 298-302) that they cannot possibly project downward into the latter in the form of solid "roots" such as are necessary for immersion. Independent lines of reasoning lead to the same conclusion (pp. 41-3).

We arrive thus at the picture of a *crust* of comparable strength at all points at comparable levels, but of varying density, resting on a yielding support (opinion 5b, p. 43). The increase of pressure and temperature with depth renders it probable that the yielding is only in part of an elastic nature, much of it being in the nature of "plastic" solid flow, due to a great decrease of strength in the crustal materials below a certain depth (opinion 5a, p. 43).

Analysis of gravity anomalies and of pendulum deflections shows that the depth at which the strength of crustal material drops very low, that is, the base of the "crust," lies at a depth of the order of magnitude of 50 to 100 kilometers (law 9, p. 25).

This concept of the crust has, then, nothing whatever to do with such matters as, e.g., the depth to which granitic material extends at different points on the earth. It is purely mechanical and quite independent of the petrographic and structural diversity of the outer shell of the earth (opinion 6, p. 49). In contrast to the asthenosphere below, it possesses strength, that is, the power to offer resistance to deformation and to transmit long-continued stresses (opinion 3,

p. 39). But the existence of isostatic equilibrium shows that this strength is quite limited. To vertical stress differences exceeding this limit, it responds by vertical movement accompanied by horizontal transfer of matter in the asthenosphere (opinion 4, p. 39), that is, by isostatic adjustment.

2. The Mobile Belts

The next step in our reasoning is directed by properties of the great linear elements of crustal deformation, the welts and furrows.

(1) They are limited to long, relatively narrow belts which run more or less continuously for distances representing substantial fractions of the earth's circumference, such as the great Tertiary belts of mountain folding with accompanying furrows, or the East African belt of "rift valleys" with adjoining or interspersed welts (like Mt. Ruwenzori) (laws 5, p. 8; 18, p. 100; 19, p. 101).

(2) Within these belts, vertical as well as horizontal deformation of the crust has taken place on a much larger scale than without (laws 4, p. 5; 22b, p. 157).

The length and continuity of these belts points to an origin through stresses acting on the crust as a whole (opinion 13, p. 114). The fact that intense deformation is limited to them suggests that the action of crustal stresses was localized in them just as the lengthening of a steel bar under tension is localized along a small stretch of its length (p. 142) or the thickening of a rock cylinder in Adams' experiments is localized along a thinned portion of the steel casing surrounding it (opinion 17a). Because of the greater amount of yielding they show we call them mobile belts in contrast to the less mobile segments between them (opinion 2, p. 24).

(3) The location of the mobile belts has shifted repeatedly since Cambrian times, and must have done so often before (laws 36, p. 347, and 37, p. 364). Wherever erosion has gone deep enough, it is seen that at some time in the past the region in question was part of a mobile belt, suffering intense compression and metamorphism (law 13, p. 62). All regions, then, which today appear as less mobile segments, must have been mobile once. Many have assumed the rôle of mobile belts twice, three or even more times, with compression in many cases taking place in different directions. The mobility of the "mobile belts" then cannot be an inherent property but must be induced through the summation of all factors that influence the

distribution of stresses in the crust, exactly as in the case of the experiments quoted above (opinion 24b, p. 245).

(4) Shape and dimensions of furrows and of welts are relatively independent of the amount of rock matter added to or subtracted from them by external agencies. Sediment-filled troughs are not depressed deeper below the surface surrounding them than sediment-free ocean deeps; and mountain chains that never reached near enough to the surface of the sea to suffer significant erosion are no higher than such as stand on land and have suffered erosion from the beginning (law 12, p. 59). This shows that the crust is sufficiently strong to be shaped more by tangential crustal stress than by stress differences due to gravity. Gravitative adjustments merely modify the deformation produced by tangential stresses, they neither initiate nor control it (opinion 8, p. 61).

3. The Tangential Stresses

A number of facts give clues as to the nature of the tangential stresses involved in the deformation of the crust.

(1) A pattern comparable to that exhibited by the Mesozoic-Cenozoic geosynclines and the folded newer mountains as well as the rejuvenated older welts forms readily when a thin spherical shell surrounding an expandable core is ruptured by expansion of the core. This is true of the pattern as a whole as well as of its details (opinion 11, pp. 89-90; opinion 12, pp. 113-14; and opinion 14a, p. 123). The pattern as a whole consists essentially of lines radiating from a "focal bar" on one hemisphere, which become deflected at their distal ends so that they come to circumscribe a more or less irregular "segment" on the other hemisphere. The regions of the Hindu-Kush and Pamirs correspond to the short "focal bar," the larger part of the Pacific Ocean to the "segment" (law 17a, p. 99). Characteristic details are sharp deflections, "virgation" and "syntaxis," and arcs joined by "linkage" (law 16, p. 84).

Two properties of the pattern of the belts of intense orogenic deformation in Cretaceous to recent times can be reproduced in the experiment by tangential compression of a thin yielding shell: two circular belts of folding approximately at right angles to each other, with exceptional elevations at the points of juncture of the two belts, the "nodes." The circum-Pacific and the Alpine-Himalayan belts correspond to the two circles with the Pamir-Tibetan plateaus and

those of the Peruvian-Bolivian Andes representing the "nodes" (opinions 14a and 14b, pp. 123-4).

The pattern of the geosynclinal belts could be understood at once, if pictured as having been formed through tensional stresses in the crust. At first sight, this seems impossible for two reasons. The tensile strength of rocks at the surface is small and they are mostly brittle. Again, if tension played an important rôle, the structure of the mobile belts should be that of great zones of tensional fracturing, while in reality it is dominated conspicuously by the effects of tangential compression.

Second thought shows, however, that these objections are not necessarily valid. It is certain that at a depth of a few miles all rocks cease to be brittle and are capable of flowing. There is no reason why the crust as a whole should not behave as a rod of steel does when placed under slowly applied tension (p. 142). If, furthermore, times of tension were to be followed by times of compression the results of the latter would supersede and in part destroy the structures produced by the former. If, finally, the present be a time of compression, the structures produced by compression would dominate the picture as we now see it.

(2) The most conspicuous and most characteristic structures produced by crustal compression, folds and thrust faults, occur in typical and large developments exclusively on the edges of and within sediment-filled furrows, the "geosynclines" (law 8, p. 15). In all typical cases great thicknesses of sediments accumulated in the geosynclines before crustal compression produced recognizable structural results. In many geosynclines, furthermore, pure limestones were deposited to a thickness of many thousands of feet, such as the Cambro-Ordovician limestones of the Appalachian and Arbuckle geosynclines and the "Hochgebirgskalke" of the Alpine belt. In such cases, obviously, troughs a mile or more in depth came into existence without compensatory welts rising alongside. The Cretaceous and Tertiary formations of the Gulf Coast show, furthermore, that even fine-grained clastics can pile up in great thickness in a given depression without a young mountain range rising parallel with it to supply the sediments.

The assumption, then, that furrows arise as a necessary complement to rising welts is not adequate. Some furrows, at least, must form independently by quite a different process.

Great thicknesses of limestones and of fine-grained clastic sediments characterize the early or geosynclinal phase of the history of all mobile belts. Coarse clastics and rapid sedimentation, leading to a filling up of the geosyncline and to alluvial deposits, distinguish the later, or orogenic phase of their history (law 20, p. 126).

These relations suggest a contrast in the behavior of the crust during the earlier and the later phases of the history of a mobile belt. Since the later phase obviously is one of compression, the earlier may be interpreted as due to tensile stresses in the crust. Such an interpretation would have to assume that geosynclines, and furrows in general, come into existence first, as zones of yielding, aligned after the pattern of tensile failure of a thin spherical shell. The tensile stresses in the crust would be ascribed to an increase in volume of subcrustal matter. A later change from subcrustal expansion to contraction would subject the crust to compressive stresses.

(3) A third property of the mobile belts points rather definitely in the direction of such an interpretation. It is the remarkable way in which new mobile belts may come into existence intersecting the older trend lines at all angles (law 36, p. 347).

It is difficult to see, for instance, how a permanent state of accumulating compressive stresses can have caused the Mississippi embayment to form nearly at right angles to the Paleozoic folds of the Ouachitas, or the sub-Betic and Betic geosyncline of Spain to cut across the Paleozoic folds of the Sierra Morena (pp. 354-65). If, on the other hand, the new furrows were the result of the stretching of the crust, a tearing as it were across the earlier trend lines, the structural relations in these and all similar cases would be readily understood (opinion 29, p. 365; opinion 33, p. 417).

(4) In any given region the stratigraphic and structural relations prove that the times of orogenic deformation were short episodes, each comprising but a relatively small fraction of a period estimated at from a tenth to a fiftieth of the time comprised by the average period (law 39, p. 382; opinion 31, p. 405). If the deformation of the crust were the result of a permanent state of compression, the crust might be expected to yield now here, then there, with the records of local movements scattered irregularly through time. The more detailed stratigraphic knowledge becomes, the more evident should this scattering become.

The opposite seems to be true, however, so far as can be told in the present primitive state of knowledge concerning world-wide correlation. It seems that most orogenic episodes for which accurate timing is possible, fall into relatively few and short divisions of geologic time (law 40, p. 384; opinion 32, p. 415).

This observation, so far as it is true, suggests strongly that there is a tendency toward world-wide orogenic crises which are dynamically different from the longer times that separate them. This suggestion is borne out by a more striking fact.

The times of major orogenic movements were also times of epeirogenic movements which caused the seas to recede widely from the continents. The longer times of orogenic quiet and of geosynclinal sinking were also times wherein the seas transgressed widely over the continents. In other words, epochs of rising mountain folds coincide with times of increased crustal relief, of continents rising with reference to sea level, in contrast with the longer intervals of time between orogenic epochs, characterized by the sinking of geosynclines and of continents with reference to sea level (law 44, p. 428; opinion 36, p. 439).

Here is a definite antithesis of two processes: one producing an increase in the crustal relief, the other a decrease. The former causes negative movements of the strand line, the latter positive movements (opinion 35, p. 421). In spite of many, sometimes large irregularities, these movements of the strand line have affected, in a large way, all continents in the same sense at the same time (law 43, p. 418). Because of its association with typical mountain folding, one must be associated with compressive stresses in the crust. In order to produce opposite effects, the other must represent the opposite kind of stress, tensional stress.

Perhaps this conclusion is not as inevitable as it appears to the writer. Yet, the facts on which it is based justify at least its adoption as a working hypothesis (opinions 15a and c, p. 141).

The alternation of opposing types of stresses carries with it all the possibilities of reversals of radial movement characteristic of the diastrophic history of all parts of the earth's surface (law 2).

(5) Two further properties of the mobile belts yield information concerning physical changes which control diastrophism. In the case of both orogenic and epeirogenic movements, which we have just interpreted as taking place approximately simultaneously and in the

same sense with reference to sea level, there is abundant evidence that the dominant movement was again and again interrupted by a smaller movement in the opposite direction. Thus, periods of dominant sinking, in geosynclines as well as in epeiric seas, were interrupted by brief episodes of uplift; and dominant uplift was repeatedly changed, temporarily, to depression. This is amply borne out by stratigraphic data for the geologic past and by physiographic observations for later Cenozoic time (law 20, p. 126; opinion 15b, p. 141). For example, the repeated minor episodes of compression during times of dominant tension renewed the supply of sediments within the geosynclines, each renewal beginning with coarse-grained detritus. The way the marine and terrestrial sediments interfinger along receding shorelines reveals the corresponding oscillation in the case of times of growing compression.

It is not possible to tell in most cases if these minor oscillations occurred simultaneously over large parts of the earth or if they were only local. They may well have been purely local, in contrast to the larger dominant movements which seem to have been practically contemporaneous over the whole earth (opinion 32, p. 415). From this we may conclude that there must be something about this alternating process of subcrustal expansion and contraction which causes it to lose and gain incessantly, with the algebraic sum now positive, now negative. This delicate balance of gain and loss may involve heat as one of the factors. In fact, the whole dualism of expanding and contracting movements recalls the homely example of the rising and falling lid on a steaming teakettle. The suspicion that heat is an important factor in this process is strengthened by another observation.

(6) Since Archeozoic time, the width of the belts in which metamorphic rocks were produced approximately at or above sea level during any given orogenic phase, has grown progressively narrower (law 42). For earlier eras the position of sea level is indicated by peneplanation and especially by planes of marine transgression. To quote merely the two extremes: Everywhere on the face of the earth where Proterozoic sediments rest with angular unconformity on Archeozoic sediments, the latter are seen to be metamorphic. If, on the other hand, all welts made during Cenozoic time were baselevelled, that portion of them within which Mesozoic sediments suffered metamorphism would represent but a very small fraction of the present land surface. Between these two extremes lie the broader zones of

metamorphic rocks produced during orogenic epochs in Proterozoic, early and late Paleozoic time. The conclusion seems inevitable that in Archeozoic time crustal folding took place more readily and that metamorphism could be produced with greater ease at comparable depths beneath the surface than now.

With this goes another peculiarity of the Archeozoic. In contrast to all later times, its structures are characterized by the abundant and widespread occurrence of concordant acid intrusives (law 34, p. 283; opinion 26, pp. 296-7). Their presence unquestionably has much to do with the practically universal metamorphism of all sediments. Somehow it must have been easier for acid magmas during the earliest recorded times to rise and spread far and wide as sills in the folding sediments than it has been ever since.

These remarkable facts lead rather definitely to the inference that in Archeozoic time the heat content of the crust was materially greater than it is now and has grown progressively, though not steadily less (opinion 34, p. 420). This inference agrees so well with that drawn above from entirely independent data that we are justified in combining the two into the following hypothetical conclusions: Fluctuations in the heat content of the subcrustal body of the earth constitute one of the factors which control the alternating contraction and expansion of subcrustal matter. Since Archeozoic time the heat content of the crust has decreased materially.

Our reasoning has lead to the following five hypothetical conclusions, of which the first four are of fundamental importance:

(1) There is a relatively strong crust overlying a relatively weak asthenosphere.

(2) The crust is strong enough to transmit tangential stresses which are the chief cause of crustal deformation; it is weak enough to tend toward isostatic equilibrium.

(3) The crust is subject alternately to tensile and to compressive stresses, caused by alternating swelling and shrinking of subcrustal matter.

(4) Fluctuations in the heat content of the subcrustal body of the earth constitute one of the factors which control the alternating contraction and expansion of subcrustal matter.

(5) Since Archeozoic time the heat content of the crust has decreased materially.

Together these statements form a hypothetical picture in terms of which all facts of geotectonics known to the writer may be interpreted without the introduction of extraneous auxiliary assumptions.

4. Tensile Phase of Crustal Deformation

In the following pages the structural changes which occur in the course of development of a typical mobile belt are described in terms of the concepts developed above.

A new mobile belt is thought to come into existence as a line of furrows marking a zone along which the crust yields under the prevailing tensile stresses. If it were brittle, taken as a whole, the crust would yield by tearing, the fractures forming the pattern which is characteristic of a sphere failing under tension. When a plate or sheet of material tears under tensional stress, the line of fractures need not be continuous. It may consist of shorter fractures *en échelon.* It may send off the blind branches in "virgation," or such branches may reunite in "syntaxis," enclosing a fragment of the crust and thus isolating it.

But the crust is not brittle. All but the outermost portion will stretch and thin before it tears, as a steel bar does under tension (p. 142). The belts of yielding are belts of prospective tearing and display the same pattern as the latter. The inert outermost part will adjust itself by faulting and flexing. Since fracturing along vertical fault planes under tension alone is impossible in the presence of any overburden, the faults in the outermost few miles of the crust will show dips as low as 45°.

At greater depths, the angle of dip of fracture planes must be still lower tending toward horizontality, that is, the direction in which the tensile stresses are applied. At any point in the crust, instead of a few large faults, innumerable minute displacements along joint surfaces may take up the sag and stretching within a belt of yielding.

While the crust is thus under tension, the materials of the asthenosphere must be under the heavy pressure of an expanding plastic core encased in a strong shell. Whenever tearing and fracturing occurs near the base of the crust, resulting pressure differences may cause local liquefactions. The great subcrustal pressures must cause such local heavy magmas to be forced up into the crust, the action being more or less comparable to that of a filter press. Relatively heavy materials derived from below the base of the crust may thus

be forced up into it so far as such bodies of liquid magma come into existence locally (opinion 21, p. 223). Basic, often extremely basic, magmas appear correspondingly as intrusive bodies, chiefly sills, within the thick sediments which fill many of the great geosynclines (law 29a, p. 268). Outside the mobile belts, they tend to appear near the surface as a network of dikes wherever larger areas undergo sinking (law 10, p. 44). Such occurrences as the dikes in coal mines of southern Illinois show that the number of such basic dikes must be much greater at depth than at the surface (p. 357).

Along major fracture lines the basic lava may even pour out on the surface, piling up lava sheets in great thickness.

The addition of such basic material to the crust increases the density of the crustal units undergoing stretching, balancing at least in part the gravity deficiency created by the thinning of the crust (opinion 22, p. 223). This effect is hardly required, however, since the times of crustal tension appear to have been generally times of least response to deviations from isostatic equilibrium. They were the times in which profound erosion succeeded in baselevelling large sections of the continents without causing recognizable isostatic adjustments.

In spite of the areal increase in the earth's surface due to subcrustal expansion, the seas transgressed over the continents far and wide in typical epochs of crustal tension (laws 43, p. 418; 44, p. 428). It is as if there had been a decrease in the capacity of the ocean basins, that is, a decrease in the vertical distance between ocean floors and continental platforms. Such a change is implied, in fact, in our fundamental assumptions. If times of subcrustal expansion are times of increased heat content of the crust, the critical temperature which defines the base of the crust, must lie nearer the surface than at times of subcrustal contraction. In changing from the latter to the former the crust as a whole must become thinner as its basal portions lose their strength through the rising temperatures. Shortening of columns of different density and correspondingly different height, which were at first in isostatic equilibrium, requires adjustment to different positions in such a way that the vertical relief at the surface is decreased. This agrees, thus, with the geologic record. This adjustment takes place chiefly between the largest units concerned, the ocean floors and the continents (opinion 37, p. 442).

5. Compressive Phase of Crustal Deformation

When the volume of subcrustal matter begins to decrease, compressive stresses take the place of the former tensile stresses. If the crust were absolutely homogeneous in thickness and substance, it might yield by thickening uniformly throughout. As the crust is heterogeneous, differential stresses are set up and yielding becomes localized along lines of weakness. Here the furrows play a dominant part. Where the surface of the crystalline body of the crust bends down into the furrows, some of the stresses remain unbalanced and movement is induced. Thus the crust begins to yield along the borders of furrows (opinion 17, p. 161).

At the surface, the deformation takes the form of a rising welt. The crust thickens, the welt rising after the fashion of a "plastic" substance (law 23, p. 199; opinion 18, p. 200). Differential upward movements within the mass, combined with the horizontal shortening due to the compression produces the folding of the crystalline core, creating a series of secondary welts as it were. This we may call "crustal" folding.

On the edge of the furrow, some of the stresses remain unbalanced and the matter of the welt begins to move horizontally out into the furrow. In that direction differential movements within the welt sooner or later cause tearing along shear fractures, with the faster-moving parts advancing outward as thrust sheets. Such thrust faults are at first purely local with the thrust sheets advancing outward in the fashion of short tongues. As compression progresses, they may become major features, carrying piles of thrust sheets far out onto the furrow along long stretches of the advancing front.

The plastic rise of the welt sets up local horizontal stresses in the adjoining crust shearing off, sooner or later, slices of the crust a few thousand or even tens of thousands of feet thick and throwing them into folds and thrust sheets, as a shovel thrust into snow shears off an outer layer and throws it into wrinkles or thrust slices, depending on the consistency of the snow. These are the belts of superficial "marginal" folding which surround larger welts (laws 21, p. 151; 22, p. 157; opinion 16, p. 147).

In the case of extreme crustal folding, the secondary welts may be drawn out "plastically" into long tongues (*decken*) pressing forward together in recumbent position, as seen in the Swiss Alps. The

"plastic" behavior during deformation and the complicated nature of internal differential movements tend to produce a pattern of folding which suggests far greater crustal shortening than actually occurred (opinion 23, p. 240).

According to the concepts on which this hypothetical picture of diastrophism rests, all crustal folding is the result of a shortening of the crust. Such shortening is only possible, however, by eliminating matter from the whole thickness of the crust, that is, from 50 to 100 kilometers depth. It is obvious, that the amount of material that was forced upward even in the most intense crustal folding is a very small fraction of the matter that must have been expelled from the former limits of the crust (law 24, p. 211). The bulk then, must have been forced downward. This conclusion is in harmony with our basic assumption. To the extent that the crust possesses strength, it will support a part of its weight. As the subcrustal matter shrinks a downward pressure gradient is created which permits the expulsion of crustal matter into subcrustal space. Instead of the crust thickening as a whole and sagging down to take up the shrinkage, matter is expelled along the relatively narrow zones of weakness, the mobile zones (opinion 19, p. 214).

As the crustal and subcrustal temperatures drop in the course of this shrinkage, the level at which the rock materials lose most of their strength is lowered also, that is, the crust increases in thickness and in strength. A stronger crust can support a larger part of its weight. Correspondingly, the decrease in subcrustal pressures becomes such that, in spite of the addition of matter that is forced downward, the internal friction within the asthenosphere is reduced. It responds more readily to differences in the weight of crustal units. Isostatic adjustment becomes more delicate. Before it has had time to spread uniformly, while it forms still a localized mass near the active mobile belts, the lighter matter which was forced downward into subcrustal space loses its mobility as the crustal temperatures drop, and becomes again part of the crust, decreasing the average density of adjoining crustal parts. It contributes in that way directly to the lower average density of the adjoining continental areas as will be seen later.

The more delicate response of subcrustal matter causes eventually widespread isostatic adjustments. The continental surfaces rise with reference to the ocean floors. There is a general regression of all

epeiric seas and the rising continents are fringed by a stairway of coastal terraces (law 43).

As the crust thickens and supports more of its own weight, and as the asthenosphere becomes concurrently more mobile, isostatic adjustment becomes more and more important. While in the earlier phases of dominant crustal shrinkage horizontal movements, folding and thrusting, were most conspicuous, in the later phases vertical uplift dominates (p. 448).

Because of the growing strength of the crust, isostatic adjustments must always lag well behind the process of crustal shortening. While crustal shortening is going on, there is always a subcrustal welt of recently expelled relatively light material along the belts of active yielding which has not yet had time to spread laterally. Apparently isostatic adjustment is delayed along the active welt itself by the very force which drives crustal matter into subcrustal space (opinion 20, pp. 218 and 219).

Gravity surveys, at such times, find belts of excessive negative anomalies such as Meinesz has recently shown to exist in the Netherlands East Indies and which seem to be present in other regions of active crustal shortening (law 25, p. 218). The presence of such belts of excessive negative anomalies, the dominance of the vertical uplift in the orogeny of the immediate geological past, general emergence of all continents and regression of epeiric seas, all show that the present represents a late stage in a compressional phase of crustal deformation. It is but natural, therefore, that we should be unduly impressed with the part which compression plays in diastrophism.

A few details remain to be added to complete the picture of the compressive phase of crustal deformation. Crustal shortening is thought to take place by expelling crustal matter downward as well as upward. It is to be expected that the proportion of crustal matter that is forced upward will vary from point to point. This accounts for the great variation of deformation, lateral as well as upward, from point to point along all mobile belts. On the whole, the upward and outward movement is the greater, the lower the bottom of a furrow lies with reference to the adjoining crust. In other words, the greater the initial dip of the surface of the crust, the greater the upward movement. As the depth of furrows varies greatly from point to point after the fashion of all lines of tensional yielding, the height of welts rising along their sides varies correspondingly (law 7, p. 14). This

may explain why the highest elevations lie close to the deepest depressions on the present surface and why the most intense mountain folding is found associated with very thick sediments, that is, with very deep geosynclines.

The tendency toward asymmetrical structure in all welts follows as a necessary consequence from the process of crustal folding as here described (law 26, p. 259).

This asymmetry may go so far, that one side of a welt alone shows active crustal folding and thrusting while the other is merely a sort of dip slope, the surface of the crust sloping back from the crest of the welt to the level of the hinterland. This tendency toward asymmetric structure is strongest on the convex side of arcuate welts (law 27, p. 260).

It seems also inevitable that at least at greater depth within the mobile zones the heat of friction should locally produce liquefaction. But as the largest part of the materials within a mobile zone under compression is forced downward, only such liquefied materials as originate relatively high in the crust will be able to work their way upward, as the most mobile of the materials undergoing "plastic" deformation. Relatively acid materials thus make their appearance typically in belts that are being lifted above the normal level of their surroundings (law 10, p. 44; opinion 25, p. 296).

Following at first the more or less inclined planes of differential movement within the asymmetrical mobile zone, creeping upward in a direction more or less parallel with the planes of flowage, the rising magma finds independent paths as it approaches nearer the surface to levels where the mobility of the surrounding rocks becomes low. Here they break across the structures through the gravitative settling of disjointed blocks of the inert crust rather than through the action of crustal stresses, exchanging places with solid rock until apparently something inherent in the process of this last, discordant advance generally stops further rise short of the surface (laws 29, p. 268; 31, p. 274; 32, p. 274; 33, p. 282; opinion 26, pp. 296-7). The increased loss of heat as the surface is approached may explain this rather general failure of the body of the magma to reach the surface.

The nearer the rising acid magma comes to the surface; the greater is the probability that secondary fractures produced by torsion of the rigid surface incident to orogeny will tap the magma and produce volcanic eruptions.

There is good reason to think that in all asymmetric welts, especially in strongly arcuate welts, the body of the mobile zone extends downward quite obliquely (law 30, p. 273). In such cases, volcanic activity will take place outside the welt proper, on the concave side of the arcuate welts, and later erosion will similarly expose the intrusive bodies lodged on one side of the asymmetrical axis.

Since torsion and consequent normal fracturing and faulting may arise within the crust under tensional as well as compressional stresses, normal faulting may take place anywhere in the crust at any time. If it extends downward sufficiently, volcanic phenomena may follow. Neither normal faulting nor volcanism bear definite enough relations to the major processes of diastrophism to be used readily in their analysis.

Something remains to be said concerning details in the pattern of folded mobile belts. Arcuate forms come into existence in two ways. The curves and sharp bends in the trend of the axis of a welt generally follow faithfully the corresponding trend of the axis of the geosyncline which by its presence caused the welt to come into existence. That these major curves are not the result of a secondary deformation of an originally straight welt is proven conclusively by the absence of all signs of intense differential horizontal movements in the hinterland of folding (law 25, p. 218), without which such secondary deformation is impossible.

In the foreland on the other hand, local overthrusting and outward movement of the welt produces localized centers of folding around which the marginal folds swing in concentric folds. Such arcuate patterns are superficial and due solely to the act of crustal folding.

The same distinction holds good for abrupt turns and deflections. In the course of the marginal folding of the sedimentary cover, bodies of crystalline rocks which rise in the foreland as swells above the average level of the base of the sediments, act as "rigid" obstacles or buttresses, and often cause conspicuous deflections in the course of the superficial marginal folds and thrust faults (opinion 24a, p. 244).

Deflections in the trend of the mobile belts themselves, on the other hand, owe their origin to causes that lie hidden in the irregularities of the crust throughout its whole thickness. Where the crystalline substructure of the foreland opposite such points of abrupt deflection lies exposed, its structure and rock materials differ in no

way from that which come to light in the old crystalline cores of the welts themselves. It is not possible to point to properties which would render the foreland "rigid," other than the algebraic summation of stresses over large parts of the crust, if not the crust as a whole. In such cases, it is as idle to look for the deflecting "rigid buttress" as it would be to look for the obstacle that causes a sharp turn in a crack in an asphalt pavement (opinion 24b, p. 245).

At the end of this discussion of the compressive phase of diastrophism, attention may be called to the behavior of the crust when subcrustal expansion again begins to dominate after a prolonged period of subcrustal contraction. Yielding tends to continue along the older lines, with furrows deepening alongside the newly created welts, the axes of the new geosynclines appearing shifted with reference to those of the original geosynclines before crustal folding (law 37, p. 364). Here and there, however, new furrows come into existence, often cutting sharply across the trend lines of earlier orogeny (law 36, p. 347). As some of these newer furrows take up part of the stresses, parts of older ones cease to function. In this fashion eventually new mobile belts come into existence while whole systems of older ones become defunct.

When, however, the pattern of such an older system as that of the late Paleozoic mobile belt is compared with that of a newer one, for instance that of the late Mesozoic-Cenozoic Alpine system, the general pattern of the latter is found to resemble that of the older system in a striking way in spite of its mechanical independence, which allows it to cut across the lines of the older at many places (law 38, p. 372). This is exactly what should be expected when the same shell with all its peculiarities is subjected repeatedly to the same process of deformation (opinion 30, p. 382).

6. Types of Mobile Belts

So far this summary has dealt only with more or less imaginary "typical" furrows (geosynclines) and welts for which the Appalachians and the Western Alps served more or less as types. But units such as these comprise only a small portion of the past and present mobile belts of the earth.

Even within the typical welts not all parts were affected in the same way or to the same degree or at all during the same orogenic episodes. How and when any given portion of a mobile belt is affected

depends at every moment on the summation of all stress differences from point to point over the whole crust.

When we turn from the few "typical" belts to the others (law 35), the differences of behavior assume such magnitude that radically different processes are commonly assumed to account for belts which may all be understood as expressions of the same processes (opinions 27 and 28, p. 347).

The term "homogeneous" has been proposed for what has just been called "typical mobile belts." A homogeneous geosyncline shows a marked uniformity of sedimentation for long distances along the strike of the furrow. Stratigraphic differences appear only gradually in the direction of the strike and, broadly speaking, the furrow behaves much like a unit. Correspondingly, it reacts rather uniformly under compression. When thrown into marginal folds, individual folds and thrust faults can be traced for tens or hundreds of miles. The type of structure ultimately produced in it by the thrust exerted by the adjoining welt, is materially the same from end to end. Normal faulting, and with it volcanism, is practically absent.

This type grades into what has been called the "heterogeneous" type. A "heterogeneous" geosynclinal belt, as the name indicates, is not a unit, but consists of a mosaic of high and low blocks, bounded by normal faults and sharp flexures.

During tensional phases, individual blocks are depressed greatly, others but little. The former receive great thicknesses of sediments, the latter little or none. During compression the whole mosaic undergoes folding, the high blocks playing the rôle of welts; sediments in the depressed blocks are folded and overthrust. But strike and intensity of folding and thrusting varies greatly from place to place with the heterogeneous character of the whole belt. Volcanism enters sooner or later, introducing further complications. The rôle of high and low blocks is not fixed. It may change repeatedly.

The heterogeneous mobile belts grade insensibly into fracture belts of low mobility. In these the tensional effects of block faulting dominate the picture of diastrophism, more or less associated with volcanism. The effect of compressional stresses is limited to the raising of moderate marginal welts, local overturning of fault planes toward the low blocks into high angle thrusts and rare minor marginal folding.

Why the tensional and compressional phases should have such different shares in these three types of mobile belts cannot be told in any specific case at present. In experiments on the fracturing of spherical shells, it is generally found that under tension as well as under compression only a few fractures of many that form at first, take up most of the ultimate deformation. It appears reasonable to assume that the same is true in the case of the earth's crust.

The same consideration applies to the curious way in which orogenic deformation proves to be independent of the depth to which the bottom of a geosyncline was depressed or the length of time sinking was in progress (law 41, p. 411).

7. Regions outside the Mobile Belts

The larger portions of the earth's surface which lie outside the mobile belts do not remain unaffected by the alternating tensile and compressive stresses. But here the effects are at a minimum. Yet at least the compressive stresses produce results which are not negligible. The repeated steepening of many of the small low domes of such regions as the Mid-Continent oil fields, as revealed by the detailed studies of drill records, may be caused by a slight regional thickening of the crust under compression.

The larger swells and basins of both continents and ocean floors are probably somehow connected with these regional stresses which are not so obviously focused along lines of action. Yet even here we see swells and basins lined up into belts, such as the axis on which the Nashville and Cincinnati swells lie.

Such a lining up of basins produces broader belts of depressions with seemingly parallel sides which, when submerged, give the appearance of shores formed by the tearing and drifting apart of a larger continental mass.

The largest units to which one might extend the terms basins and swells are the ocean basins and the continents. Of the two levels represented by the average elevations of ocean floors and continental surfaces (law 11, p. 52) only the latter are accessible to observation at the present. Wherever erosion has cut deep enough we find a substructure of intensely folded and metamorphosed rock (law 13, p. 62). This shows that the relatively high position of continental surface everywhere was brought about by the aid of orogenic movements. The complicated structure of this pre-Cambrian crystalline floor

with the pinched-in tips of synclines and the broad bases of anticlines shows that the present flat surface owes its existence to the control which sea level exerts on the external forces of degradation (opinion 9, p. 62). It is not, therefore, a mechanical counterpart of the flat portions of the sea floor (opinion 7, pp. 56-7).

It must be considered possible that the continents actually reflect an original distribution of the acid materials on the earth's surface produced by the separation of the moon, as suggested by Pickering (p. 455). In that case the distribution of the continental masses must be related somehow to the dynamics of the crust at that early stage of the earth's history.

The obscure tendency of sea floors and continental surfaces to simulate a tetrahedroid pattern may be, however, a result of the assumed relatively high strength of the crust (opinion 38, p. 450). In following a shrinking core a spherical shell of sufficient residual strength might tend to a greater downward movement over the segments corresponding to potential tetrahedroid faces, creating a pressure deficiency in the areas corresponding to potential tetrahedroid edges and corners. Relatively light matter that is expelled into subcrustal space during crustal compression must spread out beneath the stronger crust. It might find its way into such areas of pressure deficiency. Having lodged there, it would become part of the crust as the sinking temperatures cause them to assume sufficient strength to become part of the crust dynamically. This would tend to decrease the density of these segments, contributing to the relative elevations which the continental platforms attain through isostatic adjustments. A suggestion in this direction is found in the distribution of the continental areas with reference to the recently active mobile belts (p. 467).

The same relation may also explain some of the cases of welts paralleling the present continental outline, while others do so only for short distances as if the structural "grain" of the outer crust influenced the details of a border line of land and sea of essentially independent origin (law 14, p. 63; opinion 10, p. 64).

This whole last section is unsatisfactory because there are fewer concrete facts on which to base reasoning. Being less spectacular, the structural details of the great platforms between the folded mountain belts have not been studied systematically, or at least such

knowledge as exists has not been focused on the larger problems of earth structure. Most of the topography of the ocean bottoms is still unknown. Geophysical, especially seismic, methods on land and the sonic depth finder at sea are the new tools which will give us a more adequate picture of the pattern into which the surface of the crystalline body of the crust has been deformed. Not until such a broader basis of fact has been created can we hope to understand the mechanics by which the crust outside the mobile belts has been molded.

Thus ends this synthesis of facts and thoughts. One aspect of it may be pointed out in closing. The practical geologist confronted with the intricacies of the structure in a mining camp or an Alpine tunnel section may find it difficult to see in perspective the details that baffle him. Secondary fractures, control by older buried structures, the "grain" of the crystalline substructure, details of magmatic differentiation products in intersecting dikes occupy his attention. He may find the picture here drawn hardly useful, if at all.

This is unfortunate but inevitable. His task is comparable to that of accounting for the details of the cracks found within one square foot of a plastered wall fissured by an earthquake shock. Here the "grain" of reinforcing wire netting in the plaster, the alignment of the supporting boards, the swelling effect of water that has entered the cracks are controlling factors. The task undertaken in this book is that of realizing the larger forces which determined the major trend of the system of fissures over the wall as a whole, which are so wholly independent of those which have prescribed the details.

For a true understanding of nature both are indispensable, the broad distant outline and the minute detail filled in at the points nearest our vision. Seeing the one in the setting and perspective of the other, creates in the inquiring mind that feeling of intense satisfaction which transforms the work of the geologist from a task into a liberating experience.

APPENDIX

LAWS

Law 1. Aside from the effects of erosion and deposition, the earth's surface deviates from the relatively simple form of an ellipsoid, to which it may be referred, through outward (upward) and inward (downward) deflections. (p. 1)

Law 2. In the progress of crustal deformation, the direction of radial displacement is reversible. (p. 2)

Law 3. In ground plan, the forms of crustal elevations and depressions represent two types. First, elevations and depressions which are essentially equidimensional (swells and basins), and second, others that show a distinct linear development with one horizontal dimension decidedly greater than the other (welts and furrows). (p. 4)

Law 4. On the present face of the earth, excessive heights and excessive depths of crustal deformation are limited to "welts" and "furrows," that is, to elevations and depressions of distinctly linear outline. (p. 5)

Law 5. On the present face of the earth, "welts" and "furrows" do not occur independently, but are closely associated and lie side by side in relatively long and narrow belts. (p. 8)

Law 6. "Welts" and "furrows" similar in form and dimensions exist at the level of the ocean bottoms as well as on the continental platforms. (p. 14)

Law 7. In modern "welts" and "furrows," the relative elevations of points varies greatly along the strike, giving rise to deeper hollows in the "furrows" and to higher groups of mountain ranges separated by sags in the "welts." (p. 14)

Law 8. Laws 1 to 7 have been valid throughout the geological past as far as can be judged from available records. (p. 15)

Corollaries:

(a) Intensely folded sediments are several times thicker than the formations of the same age in undisturbed regions. (p. 15)

(b) Excessively thick sediments form relatively narrow, elongated belts. (p. 15)

(c) The largest part of the terrigenous sediments that fill the geosynclines was derived from highlands closely adjoining them and not from the large continental lowlands of the "swells." (p. 17)

(d) Coarse waterlaid sediments, conglomerates, breccias, and arkoses, that indicate rapid erosion of rapidly risen highlands, are practically limited to geosynclinal belts (tillites of continental glacial origin excluded). (p. 18)

Law 9. In an outer shell of limited thickness on the earth, columns of unit area possess approximately the same mass, regardless of the elevation of their surfaces; that is, their densities vary inversely as their heights above a standard surface which lies between 50 and 100 kilometers below sea level. (p. 25)

Law 10. For large units of the earth's surface, the average density of the exposed igneous rocks varies roughly with the inverse of the average altitude. (p. 44)

Law 11. The frequency curve of elevations on the earth shows two pronounced maxima, corresponding to the ocean floors and to the continental platforms. (p. 52)

Law 12. "Furrows" exist similar in shape and dimensions, both filled with sediments (geosynclines of the past and present) and as hollow surface forms (furrows in oceanic deeps). Similarly, "welts" exist in the form of mountain ranges both beneath the cover of the ocean (where they never suffered degradation) and above it (exposed to erosion). (p. 59)

Law 13. At every point on the land surfaces of the earth, where a superstructure of essentially undisturbed later sediments is absent or locally cut through by erosion, a substructure of rock is shown that bears evidence of having undergone intense deformation and upward movement. (p. 62)

Law 14. In each of the continents, the larger structural lines marked by folds, foliation, thrust faults, and intrusions, exhibit a noticeable though not invariable parallelism with the borders of the continent. (p. 63)

Law 15. During any limited unit of post-Algonkian time, small compared with the whole geological record, some orogenic belts lay far from the edge of the continental platforms, and always the number of continental shores that were free from

orogenic movements was much greater than the number affected by them. (pp. 67-9)

Law 16. Viewed in detail, the pattern of the crustal folds is characterized by deflections, by virgation and syntaxis, and by linkage of individual lines. (p. 84)

Law 17a. The modern crustal folds, on one side of the globe, radiate outward from a focal point in the Hindu-Kush and Pamirs. Strong multiple branches extend out toward the west, to the southeast, and to the northeast, and weaker branches run north and across the Eurasian continent and southward into the Indian Sea. On the other side of the globe, the crustal folds encircle the Pacific Ocean. Offshoots exist in both parts. (p. 99)

Law 17b. By far the greatest extent of excessively high land (say, above 4,000 meters elevation) is found at the focal point and immediately adjoining it in the east-west trending eastern branch of the Himalayas (and the Tibetan plateau). There is only one other region comparable in widespread great uplift, the central Andes, which trend essentially north-south. These two unique regions lie not far from antipodal to each other. (p. 99)

Law 18. The modern crustal folds lie essentially within the broader belts, "compound belts" of post-Cambrian orogenesis. (p. 100)

Law 19. In most cases, where an orogenic belt is cut off by the sea, there exists across the water a corresponding truncated end of another belt which, in some ways, decidedly parallels its counterpart both in the nature of formations and the sequence of diastrophic events recorded in its structure. (p. 101)

Law 20. The typical orogenic cycle begins with geosynclinal depression and ends with a major uplift. The interval between these limiting events comprises two phases. The first phase is one essentially of quiet sinking, only occasionally interrupted by uplifts; the second phase consists of crustal foldings separated by diminishing epochs of renewed geosynclinal sinking. (p. 126)

Law 21. Folding of the Jura and Appalachian type is essentially superficial, that is, it involves only an outer fraction of the crust. (p. 151)

Law 22a. Each belt of relatively simple folding in sedimentary rocks borders on a region of the earth's crust which in the process of folding assumed the character of a "welt" or continued to rise as such, if formed during an earlier orogenic epoch. (p. 157)

Law 22b. The intensity of deformation increases toward the edge of the welt and dies out in the opposite direction. (p. 157)

Law 23. The structure of welts proves the existence of differential movements in the crystalline cores which approach the nature of "plastic" flow. The degree of "plastic" behavior within the crystalline core increases with depth. (pp. 199-200)

Law 24. The volume of the matter forced out upon the surface during an orogenic epoch is only a small fraction of the matter that had to be eliminated in order to shorten a hypothetical crust several tens of miles thick to the extent indicated by the folding of the rocks near the surface. (p. 211)

Law 25a. Within some of the mobile belts that have been active since the beginning of Cenozoic time, unusually high negative gravity anomalies exist, aligned in such a way as to form relatively narrow and long zones. (p. 218)

Law 25b. On the whole, these zones coincide neither with the axes of furrows nor of welts but take such a course that they now follow one, then the other, and again pursue an independent course. (p. 218)

Law 26. In most cases, no signs of strong horizontal differential movements are recognizable in the unfolded forelands and hinterlands of arcuate welts. (p. 259)

Law 27. The structure of all intensely folded orogenic belts is one-sided, with folding and thrusting outward from the axial welt much stronger on one side than on the other. (p. 260)

Law 28. In arcuate orogenic belts the convex side of the arc exhibits the greater amount of overfolding and thrusting and the stronger marginal folding. (p. 260)

Law 29a. Basic intrusive rocks, chiefly in the form of sills and dikes, with or without accompanying effusives, are common constituents of the sedimentary series of "homogeneous" geosynclines. (p. 268)

Law 29b. There is no corresponding development of acid intrusive rocks in sedimentary series, introduced during the geosynclinal phase. (p. 268)

Law 30. As far back as the existing geological record permits us to judge, the larger bodies of acid intrusives have approached close to the earth's surface along belts of orogenic folding. (p. 273)

Law 31. In all strongly asymmetrical orogenic belts they lie eccentrically on that side from which the folding pressure acted. (p. 274)

Law 32. By far most acid intrusives cut across the structures produced by the folding pressure in such a way as to indicate that they arrived after the folding but so shortly after, that they must bear a genetic relation to the orogenic phase. (p. 274)

Law 33. Large discordant acid intrusives are capable of penetrating the crust to points very near the surface without bursting the roof in catastrophal fashion. (p. 282)

Law 34. Where remnants of the roof of a large discordant intrusive have escaped erosion they are found to have preserved the structural relation to their surroundings which they had before the advent of the intrusive. (p. 283)

Law 35. Large concordant acid intrusives in folded sediments are widespread only in early pre-Cambrian terranes. (p. 294)

Law 36a. Among mobile belts, three types may be distinguished, as defined in the text: "homogeneous mobile belts"; "heterogeneous mobile belts"; "fracture belts of low mobility." (p. 347)

Law 36b. These types grade into each other. (p. 347)

Law 37. When in the same general region a new mobile belt comes into existence after an older one has ceased to function, the newer may intersect the older at any angle. (p. 364)

Law 38. When geosynclinal sinking is resumed after an orogenic epoch during the life of a given homogeneous belt, the axis of the new furrow tends to parallel the earlier one but appears displaced with reference to it. (p. 372)

Law 39. New mobile belts when viewed in their entirety in any larger unit of the earth's surface are found to resemble the next older (largely inactive) belts in trend and general pattern and to lie adjacent to or superimposed on them. (p. 382)

Law 40a. At any given point on the earth, the epochs of compressive deformation have occupied much less time than the intervals between them. (p. 384)

Law 40b. In some cases, unconformable later sediments prove that each act of folding occupied only a fraction of a geologic period. (p. 384)

Law 41. Orogenic movements have frequently taken place simultaneously in widely different parts of the world. (p. 411)

Law 42. Neither a specific thickness of sediments nor any specific length of time are connected with the change from quiet geosynclinal sinking and sedimentation to folding under compressive stresses. (p. 417)

Law 43. Since Archeozoic time, the number and width of geosynclinal belts have grown consistently smaller. (p. 418)

Law 44. In a large way, the major movements of the strand line, positive and negative, have affected all continents in the same sense at the same time. (p. 428)

Law 45. The great transgressions of the sea upon the continents occurred in the intervals between the larger orogenic episodes. (p. 441)

Law 46. Swells and basins similar in form and dimensions exist at the level of the ocean bottoms as well as on the continental platforms. (p. 453)

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TERMS AND TOPICS

(exclusive of biologic and stratigraphic names)

GEOGRAPHIC NAMES

AUTHORS